



EARTHWORKS

AECOM ADVISORY

Technical Report

Tailings Reduction Strategies: Fostering a Paradigm Shift in the Mining Sector

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Delivering a better world





Executive Summary



Executive Summary

Mining is a cornerstone of global industrial development, supplying essential raw materials for infrastructure, energy, and technology. Its role has become even more critical in the context of the transition to clean energy, which demands significant volumes of metals such as lithium, copper, nickel, cobalt, and rare earth elements. The extraction of these resources generates enormous quantities of waste, particularly tailings (processing residues), which are typically transported for containment in large earth embankment dams. These tailings storage facilities pose severe environmental and social challenges: they are costly to maintain, can leach acidic drainage or heavy metals into the environment, and provide very little value to offset their risks. Historically, tailings storage facilities have been associated with catastrophic failures, which have led to loss of life, ecosystem degradation, and long-term liabilities. These risks have intensified societal pressure on the mining industry to adopt lower risk and more sustainable practices, prompting industry and civil society organizations to develop global guidelines, including the Global Industry Standard on Tailings Management (GISTM) and the Initiative for Responsible Mining Assurance (IRMA), and kickstarting a movement by companies to launch their own initiatives.

Within this evolving landscape, the concept “Zero Tailings” has been observed in industry communications representing an innovative approach to minimize or eliminate the generation of tailings. The purpose of this study is to analyze the feasibility of “Zero Tailings” in mining operations, examining its technological, economic, and environmental implications. It aims to clarify the meaning of the term, evaluate its use in corporate communications, assess practical examples, and identify the mineralogical and operational factors that influence its implementation.

The central finding of this report is that, while tailings reduction is the most practical and measurable objective for most mining majors, it does not cover the complete upcycling and elimination of material implied by the term “Zero Tailings,” nor does it provide bankable routes for the safe closure and rehabilitation of legacy tailings storage facilities. This report clarifies what “Zero Tailings” represents as a theoretical horizon, identifies the factors that govern its feasibility, and proposes new terminology and metrics to track progress honestly. The framework builds on the GISTM and ICMM Tailings Reduction Roadmap (2022), distinguishing established best practices from underexplored opportunities across varying ore mineralogies, geographic contexts, and large infrastructure designs.

The concept of tailings reduction or elimination is inherently aligned with circular economy thinking, referring to mining practices aimed at eliminating or drastically reducing the generation of tailings by ensuring that all extracted materials are either fully utilized by the operation or repurposed as upcycled products. It seeks to transform waste into valuable resources through strategies such as on-site material repurposing, tailings reuse in other industries, and reprocessing of legacy deposits, along with improved disposal methods where waste products remain.

In corporate communications, mining companies use the term “Zero Tailings” and related labels – “tailings-free,” “low-waste,” or “green mining” – to signal alignment with Environmental, Social, and Governance (ESG) principles. Although no international standard formally defines the term, it features prominently in sustainability reporting. In some cases, however, these claims function more as communication instruments than as descriptions of verifiable operational outcomes, raising concerns about greenwashing.

Companies pursuing tailings reduction or elimination must account for multiple interacting factors in determining feasibility, including geological and mineralogical characteristics, requiring a systemic transformation of mining practices, integrating new technological capabilities, economic viability, and environmental risk. High-grade, homogeneous deposits with inert gangue offer more favorable conditions, while sulfide-rich ores present significant challenges due to acid mine drainage and metal leaching. In the short term, operational costs tend to increase under tailings reduction strategies, driven by investments in filtration systems, reagent-intensive processes, and specialized infrastructure. These costs can, however, be offset by long-term benefits such as reduced liabilities, lower closure costs, and new revenue streams from tailings-derived products, including low-grade primary metals, building materials, agricultural products, and industrial sulfuric acid recoverable from pyrite concentrates.

The externalized costs of failing to minimize tailings are equally consequential, if not more, than failing to valorize them. Containment failures and underperforming control measures can result in water contamination, biodiversity loss, destruction of housing and infrastructure, and loss of life. These impacts may translate into long-term liabilities for companies and society including remediation expenses, legal penalties, and reputational damage.

The feasibility of tailings valorization, however, varies markedly across the minerals critical to the



energy transition. Copper mining, for instance, typically processes ore grades between 0.5% and 2%, generating vast volumes of chemically complex residues that make full tailings elimination impractical with current technology. Similar constraints affect nickel, cobalt, and rare earth element production, where low grades and intricate mineralogy hinder complete elimination. Tailings from sulfide-associated ores present particular hurdles for achieving chemical stability, often demanding more stringent neutralization and containment. In contrast, minerals such as lithium from brines and certain industrial minerals with simpler processing routes and inert residues offer more favorable conditions for “near-zero tailings” scenarios. Emerging technologies, such as advanced flotation, bioleaching, selective hydrometallurgy, and dewatered tailings stacking, offer pathways to reduce tailings volumes, but none can guarantee total elimination. This report classifies minerals according to their tailings reduction potential to provide a systematic basis for prioritization.

Regrettably, there is no evidence of operating mines that have eliminated tailings generation across all stages of production. While significant improvements are underway through integrated solutions such as backfilling of mined-out areas, re-mining of historical deposits, and other initiatives that convert residues into industrial products for other sectors, residual waste remains unavoidable. A portion of tailings will continue to require long-term immobilization, and progress therefore depends on scaled investment in technology, robust regulatory frameworks, market incentives for reuse, and a common language for assessing performance. To that end, this report proposes a graduated terminology continuum to cross reference claims against quantifiable, auditable benchmarks. Terms such as “Near-Zero Tailings,” “Highly Reduced Tailings,” “Controlled Tailings Management,” “Conventional Tailings,” and “Heap Leach” enable simple, comparable, and realistic goals for initiatives across commodities, ore types, and settings. Industry adoption of this framework is the most immediately actionable step available towards reframing “Zero Tailings” as a guiding principle for innovation and collaboration for continuous improvement.



Contents

1.	The Scale of the Tailings Challenge	10
2.	The Mine Life Cycle and Tailings Generation	14
3.	Social and Environmental Costs of Tailings	22
4.	Defining “Zero Tailings”	26
5.	Factors Influencing Tailings Reduction Feasibility	30
5.1	Geo-metallurgical Foundations: Ore Grade and Mineralogy	33
5.2	Sulfide-Ore Tailings: Challenges for Tailings Reduction	33
5.3	Critical Minerals	36
5.4	Mineral Classification by Tailings Reduction Potential	43
6.	Engineering Tailings Reduction	50
6.1	High Utilization of Extracted Material	52
6.2	Reuse of Tailings for Alternative Applications	53
6.3	Reprocessing Legacy Tailings Deposits	54
6.4	Improvement of Tailings Disposal Methods and Locations	55
6.5	Tailings Reduction Technologies	57
7.	Economic Impact of Implementing Tailings Reduction Technologies in Mining Operations	60
8.	Framework for Evaluating Tailings Management Approaches	64
9.	Assessing Tailings Reduction Range	70
9.1	Assessing Tailings Reduction Range	70
9.2	Performance Scale and Classification by Tailings Reduction Bands	71
10.	Toward Tailings Reduction: a Strategic Pathway for Sustainable Mining	76
11.	Disclaimer	80
12.	References	84



The Scale of the Tailings Challenge

01



1. The Scale of the Tailings Challenge

The relative pace of mine waste accumulation over the coming decades is forecast to exceed the already extraordinary rate of growth in critical minerals production. As pressure mounts on the mining industry to meet demand, so too does the burden of managing the waste that extraction on that scale will generate. What managing that burden will cost, while competing with near-term incentives to maximize investor return on capital, presents huge challenges for upholding high standards for social and environmental stewardship.

For most global mining sites, mixtures of fine-grained solid materials and process fluids that remain after the extraction of valuable minerals – tailings – are the most hazardous and challenging waste streams to manage. The world currently generates an astonishing 100 billion tons of mine waste every year, of which approximately 16 billion tons (Bt) are tailings, contributing to a current global inventory of more than 280 Bt of tailings (Tayebi-Khorami et al., 2019; Baker et al., 2020; ICMM, 2025b). Most of these tailings originate from low-grade base and precious metal mining: copper (~3.4 Bt/yr) and gold (~2.4 Bt/yr) together accounted for over 60% of global annual tailings generation in 2018, with the combined cross-commodity total having grown by roughly 40% since 2010 (ICMM, 2022). While tailings typically represent smaller solid volumes of waste than overburden waste rock at mine sites, they are far more challenging to contain and immobilize due to their fine-grained, fluid-saturated composition.

These volumes are set to grow substantially. To meet the 2°C pathway set out in the Paris Agreement, the world will need to produce more than 3 billion tons of critical minerals by 2050 (Hund et al., 2020). A typical electric vehicle requires up to six times more mineral content than a vehicle powered by a traditional internal combustion engine, while an onshore wind farm may need up to nine times more mineral resources than a gas-fired power plant (IEA, 2021; Empresa de Pesquisa Energética [EPE], 2025). In production terms, mine waste from copper alone is projected to grow fourfold by 2050, generating approximately 860 billion tons of waste over that thirty-year window (Valenta et al., 2023). Continuing with copper, 90–98% of processed ore is typically removed as tailings, highlighting the disproportionate volume of waste produced relative to usable material (Kossoff et al., 2014). Embracing circular economy principles in mining could help temper this growth but will not reverse it. Even under optimistic scenarios, mining activity and the waste it generates, particularly tailings, will continue to expand through the energy transition.

Much of this trajectory is locked in by geology. Ore grades are declining steadily across most major commodities, and newly discovered deposits are typically found at greater depths with more complex and challenging mineralogy to process (Chryss et al., 2012; Cacciuttolo et al., 2022). As a consequence, mine waste is accumulating at substantially larger quantities per ton of metal yield than historical norms. Many of the ore bodies most critical for the energy transition also require water-intensive beneficiation, placing pressure on arid regions where large deposits of lithium, copper, and rare earth elements are concentrated. In regions such as the Atacama, Australian interior, and Central Asia, it is common practice to source water from rivers and aquifers (Atlas Copco, n.d.). These operational characteristics heighten risks of water resource overdraft and environmental contamination, exacerbating ecological disruption and social conflict as a result. The minerals most needed for decarbonization are, in many cases, the most challenging to extract responsibly.

The challenge extends beyond extraction. The complexity of storing these growing quantities of tailings presents significant engineering and management risks. Currently, 18.3% of active upstream tailings dams report notable stability concerns (or failure to confirm or certify stability at some point in their history), while in parallel the increasing frequency and severity of failure events is expected to escalate (Franks et al., 2021). Active tailings dams fail at much higher rates than inactive or closed facilities, and rapid increases in commodity prices tend to drive upticks in failure incidents (Franks et al., 2021; Kossoff et al., 2014; Rico et al., 2008). Yet it remains very challenging to forecast collapses or breaches using traditional point-based geotechnical methods. This poses an unacceptably high level of risk to companies both financially and in terms of social license to operate, which underscores the urgency of exploring alternatives to conventional tailings storage (Robertson et al., 2019; Whittle et al., 2022).

Beyond these technical challenges, catastrophic tailings dam failures have triggered a crisis of confidence in the mining industry, intensifying legal and regulatory requirements and increasing pressure on the sector to adopt new technologies capable of reducing or eliminating the need for large-scale impoundments. This pressure has driven the development of global initiatives, including the Initiative for Responsible Mining Assurance (IRMA, 2018), the Global Industry Standard on Tailings Management (GISTM, 2020) and Safety First (2022).



Developed by Earthworks, Safety First (2022) represents a civil society perspective on best practices for tailings storage. It outlines principles and recommendations intended to minimize catastrophic failures and protect communities and ecosystems. The framework emphasizes independent oversight, meaningful stakeholder engagement, and application of the most available and proven technologies to reduce risk. By advocating for transparency and accountability, Safety First contributes to the global dialogue on lower risk tailings management, complementing existing industry-led initiatives while challenging operators to go beyond compliance toward true risk reduction. Safety First is endorsed by 165 mining affected communities, tribal governments, environmental and human rights organizations, and academic researchers committed to global best practices for addressing social and environmental gaps in tailings management.

In parallel, the mining sector itself is increasingly investing in research, innovation, and circular economy approaches aimed at minimizing tailings generation and promoting reuse. Yet the same fundamental paradox persists: while mining is positioned as a pillar in supporting the global low-carbon economy, the expansion of mining activities may simultaneously intensify the environmental, social, and regulatory challenges which the industry seeks to address. Resolving this tension will require not only incremental improvements in dewatering, filtration, and disposal methods, but a more fundamental reexamination of how the industry manages the full lifecycle of extracted materials. Such is the landscape (Figure 1) for pursuing a mission of significant tailings reduction or elimination.

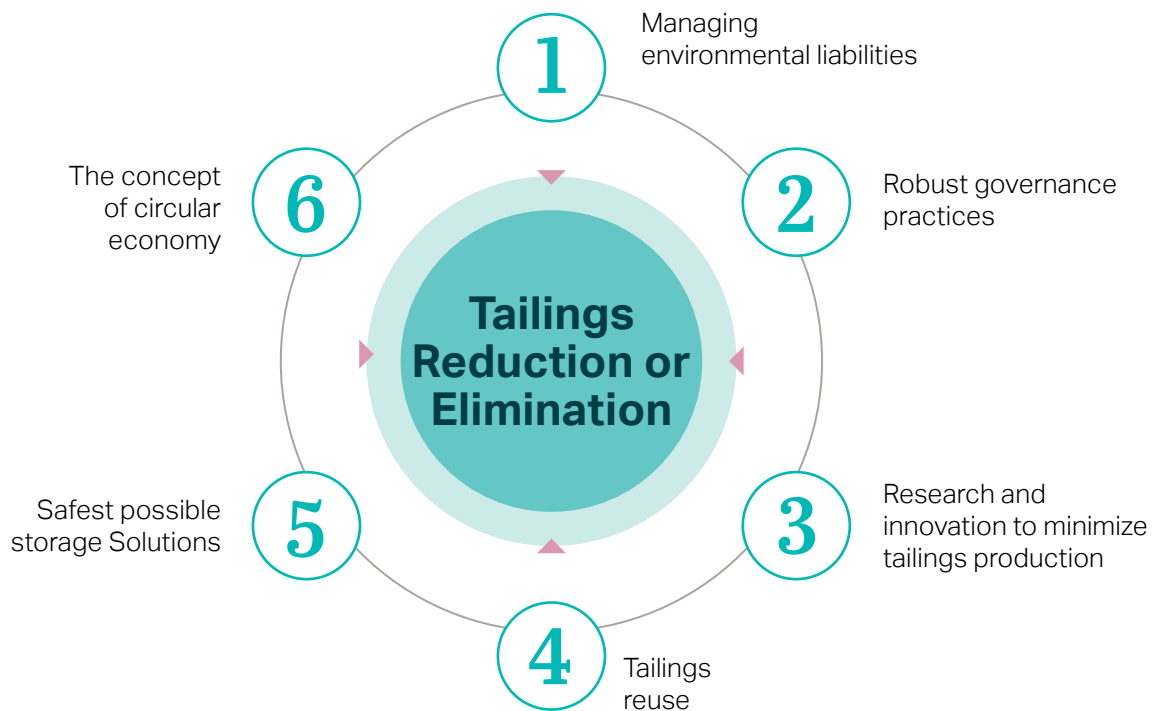


Figure 1: Conceptual framework for tailings reduction or elimination.

The Mine Life Cycle and Tailings Generation

02



2. The Mine Life Cycle and Tailings Generation

Before examining strategies for tailings reduction and reuse, it is necessary to understand how waste is generated and stored. Waste rock and tailings are inherent to mineral production, and opportunities to reduce them exist throughout the entire value chain.

In dissecting the concept of tailings produced in mining, mass balance, which has a relatively simple structure, is a helpful framework. The total mass moved corresponds to the sum of three main components:

- **Waste rock:** material excavated during mining and overburden removal activities that are below cutoff grade and have minimal economic value.
- **Tailings:** fine-grained residues generated during mineral processing stages of material above cutoff grade.
- **Final product:** the economically valuable concentrate obtained from ore processing.

Across commodities, ore bodies, and geographies, these three categories can look very different, but fundamentally remain the same in terms of mass balance. They encompass a broad spectrum of waste types including uneconomical portions of deposits, barren rocks, sediments, soils, unused fines and ultra-fines from processing, decantation sludges from effluent treatment, and even the remnants from small-scale artisanal mining (Instituto Brasileiro de Mineração [IBRAM], 2016). The diversity of these waste streams, and the environmental and social risks of their inadequate disposal, underscores the importance of understanding where they originate in the production cycle.

Figure 2 presents an infographic summarizing the archetypal mining and tailings cycle in a conventional iron ore operation, whereby the total mass extracted is equal to the sum of the masses of product, waste, and tailings.



Mining and tailings cycle

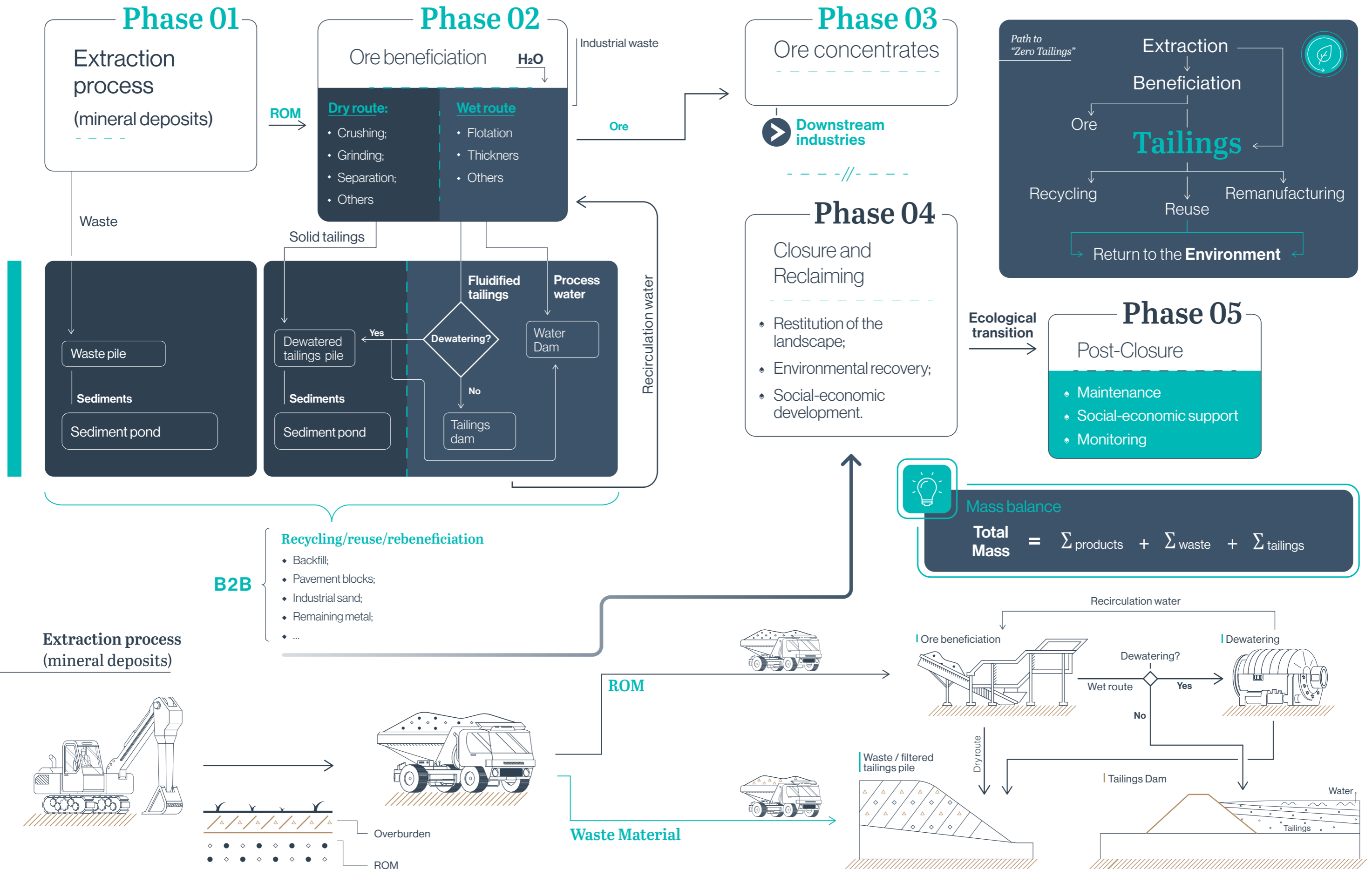


Figure 2: Infographic summarizing the typical mining and tailings cycle in a conventional operation (Iron Ore).



The **First Phase** encompasses activities within the active mining area, where virgin rock is blasted and classified, with hauling machinery designated to transport ore minerals to processing plants and waste material sent to dumps. The extracted material is typically classified into two streams:

- 1. Waste:** overburden or cave material removed alongside ore that lacks sufficient economic value to be sent to a beneficiation plant. Waste is preferentially discarded in engineered waste stockpiles, which are commonly equipped with drainage systems designed to channel fine particulate matter into dedicated sediment containment structures.
- 2. Run-of-Mine (ROM):** raw material delivered directly from the mining face to the processing plant, regardless of grade or composition. ROM undergoes a series of industrial processes designed to separate economically viable minerals from tailings.

The **Second Phase** refers to comminution, concentration of valuable minerals, and other material handling activities performed on ROM that occur at the processing plant. During mineral processing, proportions of ROM are characterized, quantified, and directed either for saleable product collection or disposal as tailings. The volume of each stream depends on feed quality and process efficiency. Accurate measurement is essential for operational planning, environmental management, and regulatory compliance in mining. These operations typically involve a range of techniques that vary depending on factors such as mineralogy, grade, and granulometry. Processing can follow two main routes:

- **The dry route**, which does not involve water and includes operations such as crushing, grinding, and magnetic separation. The dry route generates solid tailings, which are typically deposited in stockpiles, either separately or mixed with waste rock, and are often associated with sediment ponds for the containment of fine particles.
- **The wet route**, which involves water, includes hydro-cyclonic classification, flotation, thickening, filtration, and other processes. The wet route produces tailings slurries, mixtures of water and finely ground waste material. These slurries can be pumped into a tailings storage facility (TSF) or undergo further treatment, such as dewatering, thickening, and filtration. A significant portion of the water used in the processing plant can be directed to a water dam, allowing for reuse in mineral processing operations. However, most TSFs maintain low solid volume fractions due to the fluid retention of fine-grained slime particles and their rheology. For example, tailings deposited into the Zelazny Most copper TSF in Poland, Europe's largest tailings dam, contain solid volume fractions of only 7 – 9% (Jamiołkowski, 2014;

Skrzypczak et al., 2022). The high saturation content of wet tailings leads to greater stability risks.

The **Third Phase** concerns the storage and handling of ore materials for transfer to downstream industries. These may include smelting, refining, alloying and manufacturing, directing mined material far away from their source. While mineral transformation generates other byproducts as it continues along these industrial value chains, a comprehensive analysis of downstream circularity is beyond the scope of this report. As tailings are produced on-site at mines, better management of downstream byproducts from value-add industries do not directly contribute to tailings reduction or elimination objectives.

The **Fourth Phase** relates to closure and reclamation, which begins when deposits are exhausted or when economically viable minerals can no longer sustain profitable operations. Although closure occurs at the end of the mine's life, planning should begin during the permitting process and be updated throughout the mine's lifecycle. Regrettably, very rarely is this the case (Franks et al., 2021). Hence, in most cases, this phase poses significant challenges, even for mining companies that have allocated financial resources for closure. The actions required, such as deactivation of equipment, dismantling of infrastructure, stabilization of waste facilities, removal of hazardous materials, and rehabilitation of impacted areas, typically far outweigh expected costs and coincide with periods of operational downsizing, when companies have less financial margin to make necessary investments. Moreover, many of these actions are deferred in order to delay liabilities and maximize net present value, which paradoxically raises long-term closure costs and risks. Effective closure planning must also address the socioeconomic impacts associated with the end of operations, ensuring a responsible transition for affected communities. Critically, closure plans must include robust frameworks for ensuring long-term physical and chemical stability of remaining tailings storage facilities and closed assets, as well as monitoring strategies that extend well beyond the cessation of mining.

The **Fifth Phase**, post-closure stewardship, is the longest stage in the mining cycle, as it theoretically never ends. Once active operations cease, the primary obligation shifts to upholding the rigorous monitoring and safety standards implemented in the closure stage. This demands ongoing geotechnical surveillance, including instrumentation monitoring, piezometric readings, drainage performance assessments, and periodic dam safety reviews to detect early indicators of structural distress such as seepage anomalies, pore pressure changes, or slope deformation. For facilities containing chemically reactive tailings, particularly sulfide-bearing materials, monitoring must also track acid generation potential and metal mobilization over timeframes that may extend well beyond the



operational life of the mine. Water quality monitoring is equally critical: surface water, groundwater, and any seepage from tailings facilities must be sampled and assessed against regulatory thresholds to ensure that contaminant plumes do not develop or migrate into surrounding watersheds and aquifers. These monitoring obligations do not diminish with time; in many cases, the risk profile of a closed facility evolves as hydrological conditions change, vegetative covers mature or degrade, and engineered barriers age. Waste and tailings management, in particular, must be conducted with transparency and accountability, focusing either on the near-complete repurposing of tailings or on ensuring long-term dam stability, safety, and continuous monitoring.

In parallel, post-closure planning must address the redefinition of land use so that affected areas can support productive functions for host communities. However, land cannot be safely repurposed until the facilities it contains pose no credible failure modes, and storage structures cannot be considered stable unless they are compatible with the planned future use of the surrounding landscape. Reclaimed areas may ultimately serve as conservation zones, recreational spaces, agricultural land, or other community-beneficial uses, but the pathway to reuse depends on transparent engagement with local communities and regulatory authorities throughout the transition. The duration and cost of post-closure monitoring and stewardship,

potentially spanning decades or even centuries for large or reactive facilities, represents one of the strongest arguments for reducing the volume and hazard of tailings generated in the preceding phases.

Understanding the liabilities, long-term costs, and accountability associated with waste and tailings is crucial for fulfilling the commitments that mining operators make through their policies, license agreements, and public statements (Figure 3). While waste and tailings storage facilities represent a major component of these liabilities, they can also be part of the solution, particularly by providing large volumes of borrowed material that can be repurposed during the reclamation phase to support the recovery of impacted landscapes. When properly characterized and managed, these materials can be used to reshape terrain, stabilize slopes, help with flood protection, and restore the original topography in a safe and sustainable manner.

Building on this perspective, opportunities to reduce waste and tailings generation exist throughout the entire mining value chain. Therefore, the discussion must focus on making tailings reductions and repurposing technologies not only technically feasible and economically viable, but also socially and environmentally responsible. The economic dimension alone is insufficient; social and environmental considerations must also guide the transition toward reduced tailings generation.

It's important to plan ahead

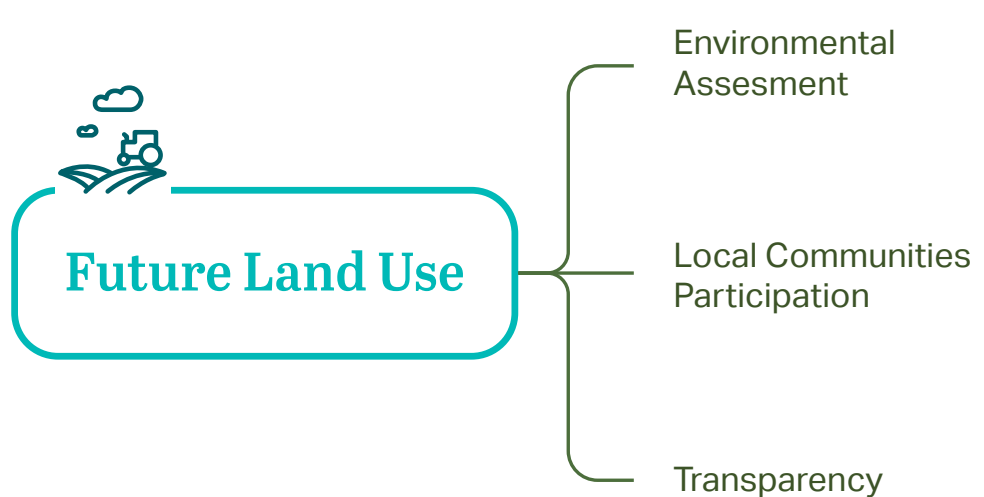


Figure 3: Key enablers of sustainable tailings management and future land use.

Social and Environmental Costs of Tailings

03



3. Social and Environmental Costs of Tailings

Mining activities can generate a wide range of liabilities that extend far beyond mine sites. The environmental and social costs of tailings – from chronic contamination to catastrophic dam failure – are borne disproportionately by the communities, ecosystems, and governments closest to mining operations. These costs vary with extraction method, ore type, and geography, but certain patterns are ubiquitous across the global mining sector.

In operational areas and their surroundings, mining frequently causes soil erosion, siltation of water courses, visual and noise pollution, and alterations to the physiochemical properties of water, resulting in harm to both aquatic and terrestrial biodiversity (Portella, 2015). Mineral exploitation also drives increased airborne particulate matter, deforestation and landscape alteration, yielding losses of ecosystem services upon which local economies and livelihoods depend. On a global scale, mining's contribution to greenhouse gas emissions through intensive fossil fuel use in machinery, transport, and processing further compounds its environmental footprint. Some estimates suggest that as much as 6% of global energy consumption is due to mineral and rock mining alone (Holmberg et al., 2017).

Tailings deposited in dammed impoundments, earth embankment structures, and stockpiles heighten the risks of soil, water, and air contamination (Portella, 2015; Palheta et al., 2023). When tailings storage facilities (TSFs) fail, the environmental impacts can be catastrophic and widespread, as demonstrated by the cases of Sino Metals Leach (Zambia, 2025), Jagersfontein (South Africa, 2022), Brumadinho (Brazil, 2019), Cadia (Australia, 2018), Mariana (Brazil, 2015), Mount Polley (Canada, 2014), among others.

From a socioeconomic perspective, mining activity has a direct impact on communities' way of life. The permanent disposal of mining waste and tailings poses perennial risks, including water and air pollution, linked to human health and environmental issues in downstream communities. Other significant impacts include property devaluation, increased local cost of living (particularly in terms of housing and food prices), reduced tourism potential, diminished water availability and quality, and restrictions on land use, such as agriculture and other forms of economic diversification.

The construction of TSFs often occurs in rural regions of the global continental interior that have been historically occupied by local populations whose livelihoods depend on agriculture, livestock farming, and, oftentimes, Indigenous cultural practices and

subsistence activities. Both the construction and multi-decadal operation of TSFs introduce land uses that can displace or restrict traditional ways of life, reducing access to essential resources and compromising local livelihoods. Agriculture, fishing, and tourism are particularly vulnerable, with disruptions resulting in income loss and, in extreme cases, forced displacement of affected populations (Assis et al., 2011; Palheta et al., 2023).

In contrast, mining operations have simultaneously emerged as the primary economic driver for many municipalities, generating public revenue, employment, inbound migration, and regional income stimulation. However, this dynamic often fosters structural economic dependency (Azevedo, 2020), exposing local populations to the volatility of mineral commodity markets and to strategic decisions made by corporate executives far removed from local realities. Price downturns typically trigger investment cuts, layoffs, and the scaling back of social and environmental programs, while upturns accelerate extraction rates. This boom-and-bust cycle means that communities and municipalities face persistent uncertainty about long-term economic sustainability, underscoring the need for strategic diversification policies that build resilience beyond the life of the mine.

The perennial existence of tailings deposits also represents an intergenerational liability, transferring to future generations the risks of structural failures and the burden of indefinite maintenance and monitoring (Barreto, 2001). From an economic perspective, these liabilities can become substantial public expenditures for the recovery and mitigation of environmental and social impacts, particularly in cases of abandonment of mining sites.

The absence of regulatory mechanisms requiring companies to provide financial guarantees, establish safe closure criteria, and conduct continuous monitoring over decades further exacerbates this vulnerability. This regulatory gap creates an imbalance between the economic benefits reaped in the present and the risks and costs transferred to the future, generating intergenerational liabilities that ultimately fall on society. Recognizing the systemic risks these legacy mining facilities represent is essential, as is the urgency of implementing public policies that ensure not only their safe operation but also their responsible and financially guaranteed decommissioning.



These costs are not only limited to conventional tailings management, as tailings reduction operations themselves carry occupational health risks and may indirectly increase CO₂ emissions. For human health, site workers face potential exposure to hazardous substances such as silica dust, sulfuric acid, cyanide or other particulates or process chemicals, which require strict monitoring and careful controls. For global environmental health, the energy-intensive processes involved in rehandling, transporting, and reprocessing stored tailings require additional equipment, fuel, and infrastructure that can partially offset environmental gains. If not properly managed and powered by mostly renewable energy, the human health and carbon footprint impacts of re-mining can be substantial, particularly in large-scale projects.

Even in the absence of conventional tailings, substantial changes to ecosystems may occur, along with intensive consumption of natural resources and the emission of particulates or liquid effluents, among other effects. Therefore, such impacts must be rigorously assessed using technical criteria, addressed through control plans, and continuously monitored. When not fully mitigable, these externalities warrant financial compensation for affected parties in accordance with legal and environmental guidelines. The adoption of integrated environmental management practices and the use of performance indicators are crucial to ensuring that the tailings reduction approach does not merely become a superficial change, but rather a meaningful transformation in the relationship between mining and the environment.

Taken together, these environmental, social, and intergenerational dimensions, compounded by the trade-offs inherent in the reduction strategies themselves, make clear that the status quo in tailings management imposes costs that are neither fully accounted for nor equitably distributed. Ensuring that tailings reduction does not merely become a superficial change, but rather a meaningful transformation in the relationship between mining and the environment, will require the kind of standardized frameworks and performance metrics examined in the remainder of this report.



Defining "Zero Tailings"

04

4. Defining “Zero Tailings”

The concept of “Zero Tailings” refers to mining practices aimed at eliminating or drastically reducing tailings generation by ensuring that all extracted materials are either fully utilized or repurposed. It is rooted in the principles of the circular economy, keeping all resources extracted from mining areas in use for as long as possible, recovering maximum value from them as goods or industrial inputs before they are discarded. While the concept holds the potential to reduce environmental liabilities and enhance resource efficiency, its practical implications are considerably more complex than the term suggests.

As stated by the International Council on Mining and Metals (ICMM, 2025a), the generation of tailings is an unavoidable aspect of mining and metals processing, and is expected to continue for the foreseeable future. To begin changing this accepted norm, it is essential to rethink the business to also include value accessory minerals present in the deposit and assign them economic value. This shift must establish a new conceptual basis for mining production, foster sector-wide commitment, and promote long-term strategic planning. To make this transition feasible, implementation must advance along multiple fronts: a) assigning tailings an economic destination as byproducts; b) reprocessing existing tailings to recover residual ore minerals and thereby reduce the pressure to expand primary mining operations; and c) deploying tailings and waste rock in mine rehabilitation, such as cave or pit backfilling and landscape restoration. By promoting the full valorization of extracted materials, an approach that promotes tailings reduction or elimination strengthens operational sustainability, fosters technological innovation and learning, and contributes to aligning the mining sector with global decarbonization and socio-environmental responsibility targets.

All of that notwithstanding, there is no standardized pathway to achieving tailings reduction or elimination across the mining sector. Each mineral deposit presents unique mineralogical characteristics, and even processing plants must be capable of adjusting their default configurations to accommodate a broader range of ore grades. For low-grade or complex mineralogy ore bodies, a phased tailings reduction strategy can create a pathway for incremental improvements that can unlock further financing through proof-of-concept studies. The same can be said of operations involving



high-value ores and production circuits compatible with more deployment-ready solutions such as filtration and material reuse technologies, which are also learning through experience to identify synergies with industries that may, but currently do not, utilize byproducts. As observed through case studies, progress on tailings reduction happens in growth spurts, enabled by the integration of engineering, innovation, new business models, and firm social and environmental commitments throughout the mining sector’s decision-making chain.

How the industry communicates about these efforts, and whether that communication accurately reflects technical reality, is a separate but equally important concern. In corporate communications, the term “Zero Tailings” and related expressions, such as “low-waste operations,” “sustainable mining,” “green mining,” “tailings minimization,” “tailings free,” and “zero waste”, are frequently adopted to reinforce commitments to ESG principles and respond to growing regulatory



and societal pressures. In some cases, however, they function more as communication instruments than as descriptions of measurable and verifiable operational outcomes.


The widespread use of expressions associated with “Zero Tailings” may pose risks of greenwashing. According to the United Nations (UN), greenwashing is a tangible obstacle to implementing sustainable solutions and systems-scale transitions. It occurs when companies or organizations prioritize slogans and narratives over clear performance indicators, verifiable reduction targets, technical evidence, effective communication, and transparency (United Nations [UN], n.d.). In such cases, progress may be overstated, technological limitations may be overlooked, and environmental and social impacts may be downplayed.

Addressing this ambiguity requires both a clearer understanding of the technical factors that determine feasibility and the development of standardized terminology and performance benchmarks to replace unverifiable claims. More than a promotional narrative, the effective adoption of a tailings reduction or elimination concept requires clear metrics, consistent technological innovation, and a genuine commitment to reducing socio-environmental impacts (Figure 4).



To Reduce and Eliminate Tailings and avoid Greenwashing

Figure 4: Key enablers for reducing and eliminating tailings.



**Factors Influencing Tailings
Reduction Feasibility**

05

5. Factors Influencing Tailings Reduction Feasibility

The feasibility of tailings reduction is not uniform across the mining sector. It depends fundamentally on the geological and mineralogical characteristics of each deposit. This chapter establishes the analytical framework by examining how ore grade and mineralogy determine the technical windows for tailings reduction (Section 5.1), then assesses the cross-cutting challenges posed by sulfide ores (Section 5.2) and the specific complexities of critical minerals for the energy transition (Section 5.3). It concludes by synthesizing

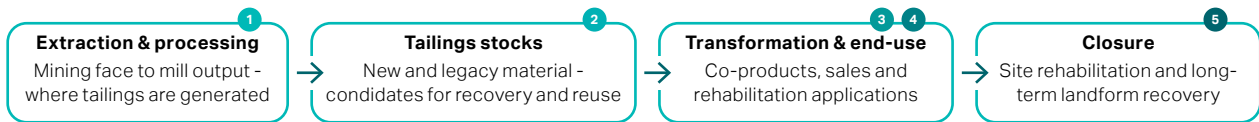
these factors into a classification of key minerals by their tailings reduction potential (Section 5.4).

The framework presented in Figure 5 comprises six metrics that are independent dimensions of measurement, not additive components of a single tailings reduction score. Each operation may contribute meaningfully to some dimensions while remaining limited on others. The framework is designed to support nuanced classification rather than ranked aggregate scoring.

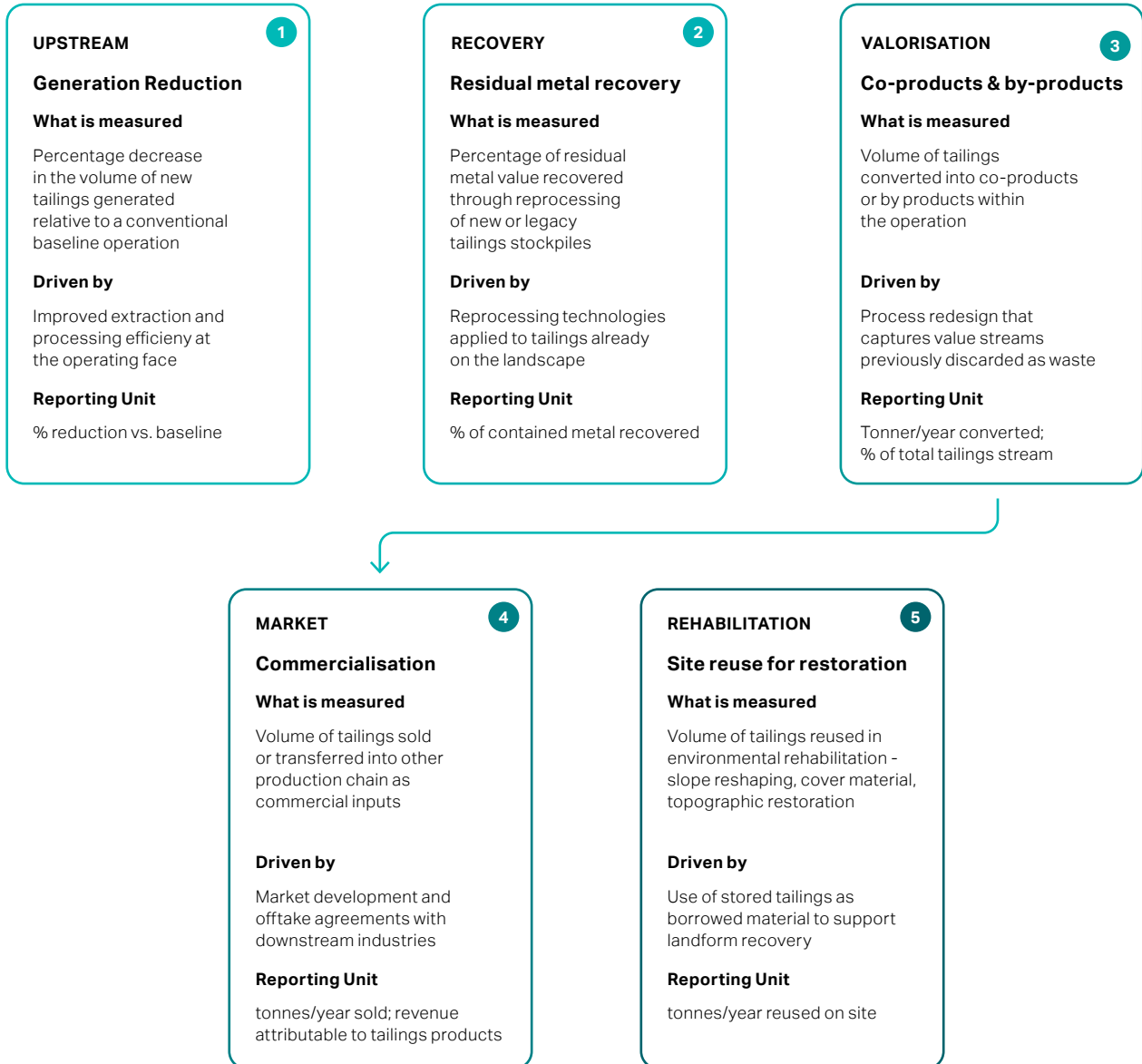




TAILINGS LIFECYCLE



PERFORMANCE METRICS



CROSS-CUTTING OVERLAY

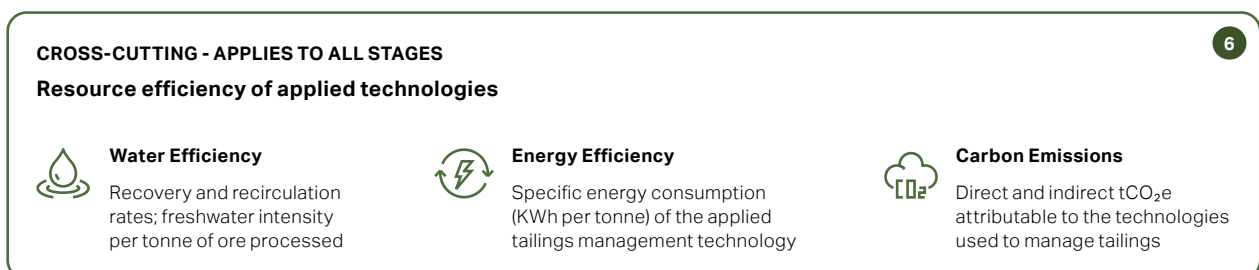


Figure 5: Tailings reduction components.





5.1 Geo-metallurgical Foundations: Ore Grade and Mineralogy

The technical and economic viability of tailings reduction initiatives is fundamentally influenced by two geo-metallurgical parameters: ore grade and mineralogy. These factors determine the potential for complete resource utilization and the extent to which tailings can be minimized or eliminated.

Ore grade, defined as the concentration of the target element within the ore, directly affects recovery efficiency and process selectivity. High-grade ores typically generate lower volumes of tailings per ton of mined material and allow for less aggressive, more energy-efficient beneficiation techniques. In such cases, tailings re-mining and consequent reduction of their mass becomes more attainable, especially when secondary minerals with commercial value are present. Low-grade deposits, however, pose greater challenges. They require processing of larger volumes of material to maintain economic viability, often resulting in increased tailings generation. Unless disruptive technologies are employed or the tailings contain recoverable elements of value, the goal of reducing or eliminating tailings may be economically unfeasible.

Mineralogy, encompassing the types of minerals present, their associations, crystal and grain size distribution, and physiochemical behavior, is equally critical. Deposits with simple mineralogy, such as high-grade hematite or well-crystallized chalcocopyrite, support efficient beneficiation with minimal waste. The presence of economically viable secondary minerals (e.g., gold in copper ore, scandium in lateritic nickel deposits, or rare earth elements in phosphate-rich zones) further enhances the potential for full resource recovery. In contrast, complex mineralogy is characterized by intricate mixtures of valuable ore minerals and other non-valuable minerals that complicate one or more stages of processing. In such cases, conventional processing often fails to achieve high recovery rates, resulting in residual fractions that are discarded as tailings. Even theoretically high-grade deposits, such as polymetallic nodules found on the ocean floor, may produce tailings and waste fractions that are removed and discarded before entering the beneficiation stages.

The interaction between ore grade and mineralogy determines the technological windows for implementing tailings reduction initiatives:

- High-grade ores with simple mineralogy are ideal scenarios, enabling near-complete resource utilization through conventional or slightly optimized technologies.
- Low-grade ores with favorable mineralogy may justify investment in selective processing routes and co-product recovery to reduce waste.

- Low-grade, complex deposits require innovative approaches, such as dense media separation, multi-stage selective flotation, advanced filtration, or integrated hydrometallurgical routes with subproduct recovery.

Across a variety of metal commodities, the single most consequential mineralogical variable limiting tailings management options is sulfide content, which is examined in the following subsection.

5.2 Sulfide-Ore Tailings: Challenges for Tailings Reduction

Economically valuable metals are commonly associated with sulfide minerals such as pyrite, chalcocopyrite, sphalerite, and arsenopyrite. Available ore processing technology produces tailings containing sulfides that, when exposed to oxygen and water, become unstable and undergo oxidation reactions. Under these conditions, metals such as Ag, As, Cd, Cu, Fe, Ni, Pb, and Zn can be solubilized and leached, resulting in acid mine drainage (AMD) and metal leaching (ML). Without proper management, these processes affect soil, surface water, and groundwater.

The reduction or elimination of sulfidic tailings presents significant technological and financial challenges. Due to their complex geochemical behavior, these materials are more difficult to repurpose, transform, reintegrate into the production process, or dispose of safely compared to non-sulfidic ores.



5.2.1 Geochemical Characterization

Geochemical characterization of tailings is a prerequisite for managing the destination (reuse, reprocessing) of both sulfidic and non-sulfidic tailings, as well as for planning their safe disposal. However, in cases involving materials with higher contamination and environmental degradation potential, this procedure becomes strategically critical.

Chemical characterization of mining residues, particularly sulfidic tailings, is crucial for evaluating the risks associated with acid mine drainage (AMD) and metal leaching (ML). International reference guides provide detailed information on essential and specialized tests for sulfidic tailings characterization and outline global best available technology. Notable examples include the Global Acid Rock Drainage (GARD) Guide (2009), developed by the International Network for Acid Prevention (INAP), the Australian Government's Leading Practice Tailings Management Handbook (Australian Government, 2016), and the "Tailings Management: Good Practice Guide" (ICMM, 2025b).

5.2.2 Safe Disposal and Management Of Sulfidic Tailings

The chemical reactivity of sulfidic tailings and their potential to generate acid mine drainage (AMD) through oxidation processes demand advanced containment, neutralization, and continuous monitoring measures. Sulfidic tailings disposal is critically assessed by international guidelines due to the risks of sulfuric acid formation and the mobilization of toxic metals (ICMM, 2025b; Oberle et al., 2020). The existing requirements significantly increase operational costs and complicate the implementation of "tailings-free" approaches.

Although the use of conventional disposal methods, such as tailings dams and stockpiles, remain widespread, their substantial environmental footprint and long-term risks require the development of lower risk and more robust alternatives. Mineral reactivity, even in co-mingled waste rock containment structures, can compromise geotechnical stability through geochemical interactions, groundwater fluctuations, and redox cycling (Hawley & Cuning, 2017). The dynamic mechanical and hydraulic properties of sulfide tailings therefore present a range of additional challenges to achieving stable disposal in contrast to the options available for deposits with low sulfide mineral deportments. Safe sulfide tailings disposal requires a systematic evaluation of both the materials and disposal site. Physical and chemical characterization of tailings, combined with geotechnical and hydrogeological site assessments, provides the basis for the design of containment structures that minimize environmental impacts. Among disposal strategies, the use of exhausted mine pit (in-pit tailings disposal, IPTD) is considered a favorable technique focused on achieving physical, hydrological, and

geochemical stability. It is recognized as a safe and sustainable strategy for mine closure (Mafra et al., 2022). According to the Mine Environment Neutral Drainage (MEND) Program (2015), in-pit disposal creates an anoxic environment that limits oxidation processes. The same source outlines generic disposal models that can be adapted to specific hydrogeological conditions and waste reactivity:

- **Dry disposal with cover:** Oxidizing waste is neutralized (e.g., with lime) and covered with barriers that restrict water infiltration and oxygen ingress, enabling physical and chemical isolation of the tailings.
- **Subaqueous disposal:** Commonly used for sulfide-rich waste, submersion prevents oxidation, thereby avoiding acid generation and metal mobilization.
- **Disposal with chemical/physical engineering:** Tailings are transformed into semi-impermeable masses (e.g., paste, geopolymers), reducing their interaction with the environment.

These solutions exemplify in-pit disposal methods and the reintegration of waste into the mining process, either as backfill material or passive containment structures. In-pit disposal aligns with the concept of tailings reduction by minimizing the generation of environmental liabilities and enabling landscape reintegration. It may also represent a lower total cost alternative when considering closure and long-term risk management. However, not all the tailings generated can be accommodated in backfill. The percentage of tailings that can be stored in backfill vary on a case-by-case basis, depending on the beneficiation method adopted, water intensity, the characteristics of the extracted mineral, and other geotechnical and operational specificities of the mining operation.

Although this approach may represent a lower risk from environmental and geotechnical perspectives compared to conventional surface storage, it still involves uncertainties regarding potential groundwater contamination. Environmental risks are strongly dependent on site-specific climatic and hydrogeological conditions. Key aspects that must be assessed include tailings geochemical characteristics and classification, interactions of tailings with groundwater and surface water, long-term hydrogeochemical evolution, pit-lake formation and stratification processes, changes in groundwater flow conditions and hydrodynamic equilibrium, and the potential hydraulic connectivity between non-inert or hazardous tailings and fractured or high-permeability aquifers.

Two alternative strategies for AMD and mine waste management have gained significant attention: preventive techniques, including oxygen barriers, bactericide application, co-disposal and blending, and



sulfide mineral passivation; and mine waste recycling, including the use of tailings in construction materials and geopolymers (Adiansyah et al., 2015; Nyström et al., 2019; Park et al., 2019). Matebese et al. (2024) reaffirm that effluent treatment and recovery technologies are complementary to these preventive approaches, advocating for the extraction of metals, nutrients, and water as means to reduce the volume of liquid and solid tailings requiring disposal. Notably, specific processes can transform sulfide tailings into value-added resources such as industrial sulfuric acid, contributing to the minimization of AMD-generating waste (Runkel et al., 2023)..

5.2.3 Emerging Technologies for Sulfide Ores

Kursunoglu (2025) provides an assessment and review of critical metal recovery from mine and mineral processing tailings, highlighting alternative technological routes that have been explored to mitigate the impacts of sulfide ore residues. According to the author, reprocessing tailings using new flotation or leaching technologies contributes to advancing toward tailings reduction initiatives by reducing waste volumes and recovering additional metal value.

The potential leaching of toxic elements limits the use of reactive tailings in civil engineering projects. However, such materials can be stabilized using cementitious binders such as Portland cement, slag, lime, and gypsum (cement paste fill). Transforming sulfide tailings into stable aggregate products, such as geopolymers or cement, can reduce contaminant mobility through controlled incorporation into construction materials (e.g., bricks, blocks, pavements) following stabilization.

Desulfurization is considered an alternative method to prevent the formation of acid mine drainage (AMD). Desulfurized tailings contain low sulfide content and therefore do not generate as much acidity. Iron sulfide particles (e.g., pyrite) can be concentrated and subsequently used as backfill material in mines or disposed of separately. Desulfurized tailings may potentially be used as cover material in mine waste storage facilities. One proposed approach involves separating conventional tailings by flotation into a sulfide-rich fraction and a low-reactivity tailings fraction (Mafra et al., 2022; Adrianto et al., 2023).

Although the desulfurization process can offer significant advantages, the economic feasibility of tailings desulfurization is site-specific and depends on factors such as sulfide content, processing requirements, operational costs, and the scale of tailings production. According to guidance from the International Council on Mining and Metals (ICMM) and the Global Acid Rock Drainage Guide, desulfurization may represent a viable mitigation strategy when evaluated within a life-of-mine perspective, particularly in cases where the long-term costs associated with





acid mine drainage prevention, water treatment, and environmental liabilities are significant. Therefore, the feasibility of this approach should be assessed as part of an integrated life-cycle cost analysis that considers both operational expenditures and long-term closure and water management obligations.

The production of sulfuric acid from pyrite tailings through roasting represents one of the most commercially promising and established pathways for upcycling sulfide waste. Pyrite roasting, the thermal decomposition of iron sulfide concentrates to produce sulfur dioxide gas, which is then converted to sulfuric acid via the contact process, was a primary source of global sulfuric acid supply until the 1970s, when cheaper elemental sulfur from oil and gas refining displaced it (Runkel et al., 2023). The technology is now being revisited as a tailings valorization strategy.

The most recent reference plant is the Eti Gubre Mazidagi complex in Turkey, a highly integrated facility that recovers cobalt, copper, zinc, gold, and silver from pyrite concentrates while simultaneously producing sulfuric acid, steam, and electric power with no CO₂ emissions (Runkel et al., 2023). Historical precedents include the Cockle Creek works in Australia, where sulfuric acid was produced from pyrite flotation concentrates as early as 1956 using turbulent layer roasting technology, with a capacity of 100 tons of acid per day (Reynolds, 1957). More recently, researchers at Lulea University of Technology have investigated the thermochemical conversion of pyrite tailings and gypsum residues from Boliden's Aitik copper mine in Sweden, demonstrating that pyrite can undergo complete decomposition into pyrrhotite and release elemental sulfur below 750°C in an inert atmosphere – products that can be further processed into sulfuric acid, direct reduced iron, and recovered lime (Elsadek et al., 2023). LKAB and Boliden signed an agreement in 2021 to produce fossil-free sulfuric acid from Aitik's pyrite waste for use in extracting rare earth elements and phosphorus from LKAB's mining waste, though the collaboration was ultimately suspended in 2025 due to cost challenges, with LKAB opting instead for sulfuric acid production from elemental sulfur (LKAB, 2024). The Aitik case illustrates both the technical promise and the economic hurdles of pyrite-to-acid pathways: the technology is proven, but achieving commercial viability depends on the scale of pyrite production, local acid market demand, and the integration of multiple revenue streams from co-products.

Another process aimed at reducing the liabilities associated with sulfide tailings involves the use of microorganisms for metal recovery from ores (biomining), as explained by Rawlings (2013). During bioleaching, metals such as copper, nickel, or zinc are oxidized through microbial action, converting water-insoluble sulfides into soluble sulfates. Advances in flotation and hydrometallurgical techniques are

highlighted by Park (2022), who emphasizes the potential to reduce tailings generation through cleaner processes (e.g., avoiding NaHS or cyanide), the recycling of ultrafine tailings, and the need for ongoing research in this field.

Achieving tailings reduction or elimination in sulfide ore contexts requires more than economically viable approaches. It demands a holistic strategy that takes into account the fraction of tailings that cannot be reused or neutralized and must be permanently confined and monitored. This reality underscores the importance of combining preventive and containment strategies with long-term stewardship, ensuring that even non-recoverable materials are managed in a way that minimizes environmental liabilities and supports responsible mine closure. These complexities make the pursuit of tailings reduction or elimination in sulfide-rich operations significantly more demanding than non-sulfide ores.

5.3 Critical Minerals

Critical minerals are resources that national governments designate as important for defense, energy transition technologies, and other essential industries which are considered vulnerable to supply chain disruption. The designation is based on which technologies governments and policy makers consider important and where each mineral's deposits and processing facilities are located, rather than on mineralogical properties or perceived scarcity. Many of these minerals are indispensable to clean energy technologies yet are generally low-grade or often associated with sulfide ore bodies, compounding extraction difficulties with the need for specialized processing flowsheets and expensive waste containment.

Among the most important critical minerals are:

- Lithium, nickel, cobalt: used in lithium-ion batteries for electric vehicles and energy storage systems.
- Rare earth elements (such as neodymium, dysprosium): essential for permanent magnets in wind turbines, electric motors, and electronic defense technologies.
- Copper and aluminum: fundamental for electricity transmission, EV wiring, and solar PV systems.
- Graphite: used in battery anodes.
- Platinum group metals: necessary for green hydrogen technologies and fuel cells, as well as specialty applications for aerospace brazing and advanced alloys.

As nations race to secure supply chains for these materials through mining, refining, and recycling, the environmental footprint of critical mineral extraction is drawing increased scrutiny. Their tailings, often chemically reactive residue left after ore processing, represent one of the most persistent and complex



environmental challenges associated with critical mineral production. As ore grades decline and mining expands into new frontiers, the volume, toxicity, and management complexity of tailings are expected to increase.

5.3.1 Critical Minerals and Their Tailings Footprint

The production of critical minerals generates a significant amount of mining waste, as most of these minerals occur in low-grade ores requiring the processing of vast quantities of rock to obtain small quantities of valuable metal. The disposal of these materials in waste dumps and tailings storage facilities pose significant environmental and social challenges, as they can cause heavy metal pollution. These challenges are especially acute in active mining areas with ongoing material handling and large-scale construction activities, and in abandoned areas with minimal oversight.

Lithium illustrates the ore-grade challenge. While a common mineral like spodumene theoretically contains 7.9% Li₂O or 3.7% lithium by weight, continental brines, such as those from the Salar de Atacama (Atacama Salt Flat) in Chile, have much lower concentrations, ranging from 0.11% to 0.305% (Evans, 2014). In comparison, lithium brines from the Wairakei geothermal field in New Zealand exhibit even lower grades, with concentrations of around 10 ppm, which is significantly below those of typical Salar deposits. The El Tatio deposit in Chile, however, offers a higher-grade example, with lithium concentrations reaching 47 ppm.

Rare earth deposits show similar patterns of even lower grades. Wall (2014) evaluated 22 rare earth mining projects and found that half of them had very low grades, below 3%. A prime example is the Kvanefjeld project in Greenland. This type of deposit, containing minerals like steenstrupine and eudialyte, has a grade of only 0.55% REO (Rare Earth Oxides).

5.3.2 Critical Minerals and Tailings: Chemical, Physical, and Operational Challenges

Three characteristics of critical mineral tailings are particularly important for the selection of reduction strategies and technologies:

- **Chemical complexity:** Tailings can contain reactive sulfides, residual processing chemicals, and even naturally occurring radioactive materials (NORMs), especially from rare earth elements and uranium deposits.
- **High water dependency:** The processes used for critical minerals are often water intensive. This increases the demand for robust tailings management systems that can mitigate water contamination and facilitate water recovery, thereby reducing overall water consumption.
- **Low recovery:** Extracting low-concentration elements from the host ore is challenging and often results in a portion of the valuable material being discarded in waste streams, which represents significant inefficiency and resource loss.

The following subsections examine how these characteristics manifest across a set of critical minerals that are highly relevant to the energy transition.





5.3.2.1 Lithium

Lithium tailings are shaped primarily by high water dependency. Lithium is sourced from two fundamentally different deposit types (brines and hard rock) each with distinct tailings profiles, both with high water demands.

In lithium mining from brine and hydrothermal deposits, the conventional Evaporation Pond Method remains widely used. In the Salar de Atacama (Atacama Salt Flat), Chile, system losses are estimated to be between 30% and 35%, yielding a lithium recovery rate of 65% to 70%. At the Salar de Olaroz project in Argentina, Orocobre estimates a 26% loss, indicating a recovery rate of 74% (Evans, 2014). Both operations exhibit a high level of mineral recovery and, consequently, a lower rate of tailings generation compared to other mineral types.

Even still, recent advancements have introduced Direct Lithium Extraction (DLE) technologies, including variants that incorporate reinjection, known as Direct Lithium Extraction with Reinjection (DLE/R), which are designed to improve lithium recovery rates.

Despite being promoted as a green alternative, DLE methods are not without environmental consequences. DLE and hybrid DLE/R both generate waste products including residual brines, saturated resins or adsorbents, and sludge. A comprehensive review by Farahbakhsh et al. (2023) revealed recovery rates of over 60% from geothermal brines. However, the production of lithium from spent geothermal brines generates significant solid waste. According to Stringfellow & Camarillo (2025), this process can yield up to 5,000 mg of metal hydroxide solids for every kilogram of brine processed, composed primarily of iron, manganese, and zinc hydroxides, with the potential to contain lead and arsenic. The purification of the lithium product requires the separation of magnesium and calcium; geothermal brines in California can contain over 25,000 mg/L of calcium, underscoring the scale of the solid waste management challenge.

Beyond brines, lithium is also mined from pegmatite deposits. The 2019 updated definitive feasibility study by Keliber Oy (now majority-owned by Sibanye-Stillwater) for the Keliber project in Finland indicates that from a nominal concentrator throughput of 600,000 tonnes per annum of spodumene-bearing ore, approximately 12,500 tonnes per annum of battery-grade lithium hydroxide (~11,000 tonnes lithium carbonate equivalent) would be produced (Keliber Oy, 2019). The remainder of the ore mass exits the process as solid byproducts – primarily quartz-feldspar sand from the concentrator and analcime sand from the chemical plant – which Keliber has identified as having potential commercial value. According to the operator, with the proper processing flowsheet and environmental controls in place, these waste streams could be upcycled as potential sources of building materials, port fill, and water treatment media.

Despite its growing importance, lithium tailings represent only approximately 1% of all mineral tailings (Oberle et al., 2020), compared to copper, which generates an estimated 8 billion tons of tailings annually, accounting for 46% of global tailings production. Although lithium's share of tailings is small, its environmental and social impacts can be disproportionately significant, particularly in arid regions where water-intensive extraction intersects with fragile ecosystems, Indigenous lands, and rural communities, raising concerns about land rights, resource access, and long-term sustainability.

5.3.2.2 Copper

Copper, one of the most extensively mined minerals required for the clean energy transition, faces significant challenges in tailings management due to the low ore grades of remaining deposits around the world. Numerous copper mining sites already contend with vast volumes of tailings, prompting the development of initiatives aimed at reducing waste generation. The tailings challenge for copper is driven overwhelmingly by low recovery – at typical ore grades of 0.5-2%, more than 98% of processed material becomes waste (Kossoff et al., 2014).

The nature of that waste and the hazard it carries turns substantially on whether the copper is bound in oxide or sulfide minerals, because the two are processed by entirely different routes. Oxide ores such as malachite, azurite and chrysocolla are leached with sulfuric acid and the copper recovered by solvent extraction and electrowinning, leaving a spent, already-oxidized residue that, while acidic from processing, has little capacity to generate further acidity over time.

Sulfide ores (chiefly chalcopyrite, with chalcocite and bornite) are instead usually concentrated by froth flotation, and their tailings are the more problematic of the two: the flotation rejects retain residual sulfides, above all pyrite, which oxidize on exposure to air and water to produce sulfuric acid and mobilize copper, arsenic and other metals as acid mine drainage, a process that can persist for decades to centuries after closure (Kossoff et al., 2014). This distinction is becoming more consequential as the oxidized and supergene-enriched caps of porphyry deposits are mined out and production shifts to deeper, lower-grade primary sulfide ore, which must be floated, simultaneously increasing the volume of slurry tailings and their long-term geochemical liability. The El Teniente tailings reprocessed at Minera Valle Central (MVC), in Chile, are themselves sulfide flotation tailings of exactly this kind. While some are exploring the bioleaching of primary sulfides, such as Endolith, Ceibo, and Nuton (a Rio Tinto venture which does so on an industrial scale) none have yet reached commercial scale of sulfide leaching with recoveries competitive to traditional flotation circuits.

In the context of sulfide tailings reprocessing, Chile provides a well-established example of industrial application. Minera Valle Central (MVC), operating since 1992 in Chile, produces copper and molybdenum concentrates with grades of approximately 0.115% and 0.009%, respectively, through the reprocessing of tailings generated by the El Teniente mine (Henderson, 2014). MVC holds the rights granted by Codelco to process both the fresh tailings from current El Teniente operations and the historical tailings stored in the Colihues and Cauquenes deposits, totaling 1.5 billion tons. Beneficiation involves grinding and multiple stages of flotation. The residual waste from these processes is currently being deposited into the voids of decommissioned open-pit mines.

5.3.2.3 Rare Earth Elements

REE tailings can present all three challenges simultaneously – chemical complexity (including NORMs), water-intensive processing, and low recovery from intricate mineralogy – but the balance among them, and the form the resulting tailings take, shifts markedly by deposit type. Rather than falling along a simple gradient from favorable to difficult, each principal deposit type – placer sands, hard-rock carbonatites and alkaline complexes, and regolith-hosted ion-adsorption clays – concentrates the burden in a different place.

In placer (heavy-mineral-sand) deposits, the bulk tailings are among the most benign in the rare earth sector: composed largely of siliceous sand and clay, they can be dewatered and returned to rehabilitate the mined landscape. The Moma Titanium Minerals Mine in Mozambique illustrates this favorable case. Although Moma is operated for titanium minerals and zircon rather than rare earths, it is a heavy-mineral-sand placer of the type in which monazite and other rare earth minerals co-occur, and its tailings practice is instructive. Sand and slimes tailings are managed through a series of settling ponds; once dried, the sand is recontoured and returned to the mined-out area, restoring the original topography. Rehabilitation is completed by planting native vegetation and food crops, and the land is returned to local communities. This approach largely eliminates the need for conventional wet tailings dams, reducing environmental risk and promoting ecosystem restoration. As the operation scales and transitions to the higher-slimes Nataka ore zone, however, a conventional TSF has become necessary, with construction commencing in 2025 (Kenmare Resources, 2024). This trajectory, from “near-zero tailings” toward conventional storage as operations mature, illustrates a pattern observed across several deposit types and underscores the limitations of extrapolating early-stage results to full-scale production.

The favorable bulk-tailings profile of placers can, however, mask a concentrated hazard in the rare earth fraction itself. Monazite, the principal rare earth

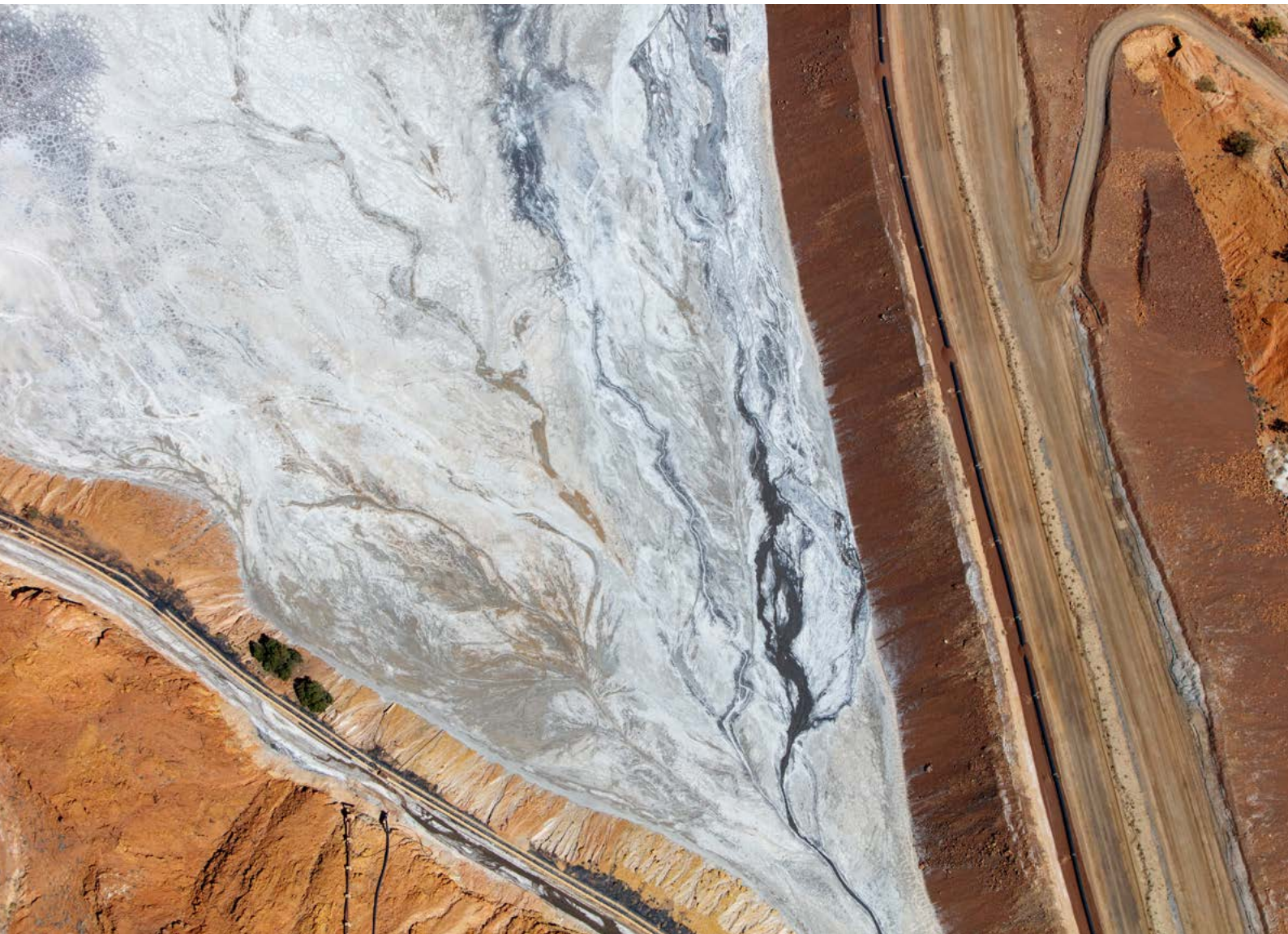




mineral in many beach and alluvial sands, often carries significant thorium and uranium, so the very stream that holds the rare earth value also holds the reactivity. At Richards Bay Minerals, operated by Rio Tinto in South Africa, monazite occurs as a byproduct of heavy mineral sand mining for zircon, ilmenite and rutile and is concentrated in the primary processing circuit (Philander & Rozendaal, 2012). While the operation has documented extensive dune-rehabilitation work – restoring and reshaping sand dunes by reintegrating the original seed bank and organic matter (Rio Tinto, 2022) – the radioactive monazite byproduct demands additional handling, storage, and due diligence. Due to the high value of the contained rare earths, their radioactivity sharply limits options for reduction, transport and storage, so that the recovered monazite concentrate is often either discarded or sold at a discount to buyers willing to shoulder the handling risk, such as countries in non-conformance with IAEA Regulations for the Safe Transport of Radioactive Material (International Atomic Energy Agency, 2025). Placers thus pair the most re-integrable bulk tailings in the REE sector with one of its most intractable NORM problems in the product stream.

Mining and processing techniques for REEs in carbonatites, alkaline rocks and hydrothermal deposits are more established than those for beach-sand placer deposits (Wall, 2014; Zhou et al., 2021), and here the dominant challenge is the volume of hard-rock tailings and the water used to manage them. The Mountain Pass deposit in California – a carbonatite deposit associated with ultrapotassic rocks and among the world’s richest, with approximately 6.0% total rare earth oxides (TREO) (MP Materials, 2025) – shows how that challenge can be addressed. MP Materials, which operates Mountain Pass, runs a dry (filtered) tailings process that it identifies as a key differentiator, enabling the site to operate as a “zero discharge” facility that recycles roughly 95% of its process water (MP Materials, 2025). It worth noting that this technique reduces not the volume of tailings but the water bound up in their storage; that reduction is nonetheless meaningful, given the gains in physical stability and the lower risk of a wet-impoundment failure that dewatered, dry-stacked tailings provide.

Regolith-hosted ion-adsorption clay (IAC) deposits represent a third and quite different case, and the



one that most clearly shows why low tailings volumes should not be equated with low impact. Formed by intense tropical weathering of rare-earth-enriched granites, these deposits host rare earths as ions loosely adsorbed onto clay minerals within shallow, laterally extensive saprolite profiles, typically at very low grades on the order of 0.05-0.5% REO (Sanematsu & Watanabe, 2016). The parent granites are typically Mesozoic, most often Jurassic to Cretaceous, but the ore resides in a far younger regolith formed by prolonged Cenozoic weathering; it is the depth and lateral reach of that weathering profile, rather than the age of the bedrock, that gives these deposits their shallow, sprawling geometry and correspondingly large surface footprint (Xie et al., 2016).

IACs are the dominant global source of heavy rare earths and yttrium and, notably, carry low thorium and uranium, so the NORM burden that defines monazite is largely absent (Sanematsu & Watanabe, 2016) and their distinct hazards lie elsewhere. Because the deposits are shallow, low-grade and sited in vegetated uplands, the historically dominant pool and heap-leaching methods required stripping vegetation and ore across large areas

– a “mountain-moving” practice associated with severe deforestation, erosion and land degradation relative to the rare earth tonnage recovered. By one widely cited estimate, producing a single ton of rare earth oxide this way, through surface mining and heap leaching, strips roughly 300 m² of vegetation and topsoil and generates on the order of 2,000 tons of tailings and 1,000 tons of ammonium-sulfate wastewater (Yang et al., 2013). In-situ leaching, now favored precisely to avoid this surface destruction, injects ammonium-sulfate solution directly into the regolith and generates little conventional tailings, but it displaces the burden into the subsurface, where ammonium and sulfate contaminate ground and surface water long after mining ceases (Yang et al., 2013), and where solution-induced clay swelling and loss of slope stability can trigger landslides (Negash et al., 2024). The IAC case is therefore the section’s clearest caution: a deposit type that produces almost no conventional tailings, and little radioactivity, can nonetheless rank among the most environmentally damaging routes to rare earth supply.



5.3.2.4 Re-mining, Reuse and Byproduct Recovery

Beyond reprocessing existing tailings, an even more fundamental inefficiency lies in the loss of critical mineral byproducts during primary commodity processing. Some critical minerals are not mined as primary commodities but are recovered or lost as byproducts of other operations.

Sarker et al. (2022) explored the recovery of lithium, cobalt, and rare earth elements (REEs) from tailings, identifying low concentration of target metals and complex mineralogical characteristics as key obstacles to reprocessing efficiency. They propose bio-hydrometallurgical methods, specifically bioleaching, as a promising solution for REEs and cobalt (see also Odimba et al., 2023, on carbonate-specific REE bioleaching), due to their lower cost and environmental impact, though the viability of applying bioleaching for lithium recovery is largely unproven. The application of REE mining waste as raw materials in the construction industry, such as in concrete and bricks, is also a promising approach. While this can reduce environmental impact and immobilize heavy metals within concrete matrices, thorough assessment of geological origin is critical due to the potential presence of NORMs (Paleologos et al., 2025).

Indium provides a notable example of unrealized circular potential: an estimated 25-30% of the 1,000 tons potentially available annually from zinc ore is recovered, with the remainder lost to waste streams due to a lack of economic viability for dedicated extraction capacity at zinc refineries or the low efficiency of existing recovery technologies (Mikolajczak & Harrower, 2012, as cited in Wall, 2014). To that end, research from the Colorado School of Mines found that U.S. mines already extract nearly every critical mineral the country needs, cobalt, lithium, gallium, rare earths, germanium, but instead of recovering them, they are discarded into tailings piles (Holley et al., 2025).

The routine loss of valuable critical minerals to tailings and processing residues in primary commodity operations reflects prevailing economic and technical constraints. In many cases, the infrastructure required to recover these secondary minerals is either not available or involves capital and energy requirements that exceed the expected returns from byproduct recovery. This dynamic is further influenced by the current structure of global markets, where processing and refining capacity for several of these materials is geographically concentrated in China, contributing to relatively low market prices and limiting the economic incentives for additional recovery capacity in other regions. At the same time, some producing regions have limited access to downstream processing facilities, which can restrict the recovery of secondary materials even when suitable feedstock is available. Within this context, tailings reduction strategies offer a pathway to

improve resource efficiency by enabling the recovery of additional value from existing material streams, while also contributing to reductions in waste volumes and associated environmental management requirements. In addition, the development of byproduct recovery capacity can act as an economic catalyst in different regions, creating new industrial activities and fostering diverse, multilateral commercial opportunities linked to the supply of critical materials.

5.3.3 How Countries Have Been Addressing Critical Mineral Tailings

Countries with a long-standing tradition in the mining sector have been actively developing new strategies to produce critical minerals for the energy transition, often in collaboration with local universities and mining companies. While approaches vary in maturity, the national strategies reviewed share common elements: public-private collaboration, national tailings inventories, circular economy framing, and targeted investment in processing innovation.

According to the Australian Government's Department of Industry, Science and Resources (2023), there is an effort to convert tailings into new products. One case study is "Towards Zero Lithium Tailings," in which Albemarle's lithium hydroxide refinery in Kemerton, Western Australia is investigating, with the support of the national government, ways to convert lithium processing tailings into new products for use in the transport and construction sectors.

The Atlas of Australian Re-mining Potential, published by Geoscience Australia (n.d.), is an interactive online tool designed to provide governments, industry stakeholders, and the public with detailed information on mine tailings, waste rock, smelter residues, and related mine waste materials. Developed by Geoscience Australia in collaboration with RMIT University, the University of Queensland, and state geological surveys, the Atlas identifies potential secondary sources of critical minerals. It supports the sustainable and economically viable recovery of these minerals from mine waste, while contributing to Australia's broader objective of achieving net-zero carbon emissions by 2050.

The Canadian Critical Minerals Strategy, as outlined on the Government of Canada's official website, aims to position the country as a global supplier of essential minerals for green and digital economies, encompassing the entire value chain from exploration to recycling. The strategy aims to close material loops by advancing recycling infrastructure, secondary markets, and the recovery of minerals from mining and industrial waste streams.

A recent report from the Action Canada Fellowship and the Public Policy Forum argues that re-mining tailings



can unlock value, strengthen supply chains, and reduce environmental liabilities. Collins et al. (2025) make three recommendations:

- Advance a National Tailings Inventory: Create a comprehensive, publicly accessible national database to identify high-potential critical mineral re-mining opportunities by standardizing data and integrating Indigenous knowledge.
- Create a Purpose-Built Policy Framework: Establish a clear regulatory and liability framework to streamline permitting and promote collaborative partnerships for re-mining projects.
- Incentivize Innovation and Partnerships: Promote the development and adoption of new tailings recovery technologies through targeted funding, and actively support Indigenous-led re-mining initiatives.

Chile’s National Lithium Strategy is designed to ensure economically, environmentally, and socially sustainable progress in the lithium industry. It acknowledges salt flats as complex and unique ecosystems, vital desert water reserves, and ancestral homes as requiring respect and safeguarding. The strategy’s key objectives include the sustainable development of lithium production, social and environmental sustainability, technological and supply chain advancement, and the objective of growing Chile’s share in lithium revenue from downstream products. A central priority involves pioneering new extraction technologies, such as direct lithium extraction with brine reinjection (DLE/R), to minimize environmental impact and enable sustainable production expansion (Chile, 2023).

Among the main initiatives developed by the Finnish government, the newly launched “Zero Waste Mining and Critical Minerals” campaign by Business Finland is seeking research projects to improve raw material availability and sustainability in the mining sector. The goal is to address future challenges, enhance international competitiveness, and reduce or eliminate waste, such as tailings, by using technologies like bioleaching and closed-loop water systems (Business Finland, 2025).

The convergence of these strategies around re-mining, circularity, and government-supported innovation suggests an emerging international consensus, though implementation remains uneven and none of the strategies reviewed sets binding tailings reduction targets.

5.3.4 Tailings Reduction Perspective for Critical Minerals

While the preceding subsections focused on the critical minerals most relevant to the energy transition, tailings reduction feasibility must be assessed across the full spectrum of mineral production. The following classification (Table 1) extends the analysis to include major commodity minerals and industrial minerals

alongside energy-transition materials, providing a comprehensive basis for strategic prioritization.

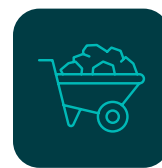
Critical minerals are typically associated with complex chemistry, fine granulometry, high water dependency, and low recovery rates – characteristics that make full tailings elimination exceptionally difficult (Figure 6). Even the most viable re-mining projects for critical mineral tailings continue to generate residual waste, confirming that no current technology has achieved 100% mineral recovery. Advancing practical tailings reduction for these minerals will require continued development of efficient processing technologies, improved geological models, and expanded markets for mining-derived byproducts in industries such as construction and agriculture.

Tailings Reduction Perspective for Critical Minerals



Demand

- The demand for critical minerals is expected to increase sixfold by 2050



Mining Waste

- Major environmental challenge
- Complex chemical composition
- High dependence on water



No project has achieved the “Zero Tailings” goal

- Technological advances are necessary

Figure 6: Tailings reduction challenges for critical minerals.

5.4 Mineral Classification by Tailings Reduction Potential

To provide a framework for the feasibility of tailings reduction techniques, mineral deposits may be grouped into four categories: High Potential, Medium Potential, Low Potential, and Very Low Potential.

The classification integrates three dimensions: (i) reuse pathways (e.g., agriculture, construction, or tailings re-mining), (ii) environmental reintegration (ranging from inert to hazardous), and (iii) overall potential for achieving significant reduction of tailings. It serves as an analytical exercise to support understanding of the technical and operational conditions that influence tailings reduction. It does not account for



Mineral / Deposit Type	Typical Grade	Rock-to-Metal Ratio (Nasser et al., 2022)	Global Tailings Share	Sulfide Assoc.?	Primary Tailings Challenge	Available Reduction Pathway	Key Limitation
High Potential							
Rare earths from placer deposits (monazite)	Variable (heavy mineral sands)	~10 ¹ (titanium host)	<1%	No	Scale limitations; radioactive Th/U in monazite concentrate	Dewatering + landscap reintegration; sand recontouring	TSFs required at production scale (e.g., Moma post-2025); radioactivity limits reuse
Crushed stone and aggregates	N/A (bulk commodity)	~1-3	Not tracked	No	Market absorption; quality specifications for construction use	Direct reuse in construction industry	Logistics cost; market resistance; perception issues
Lithium from brines	0.11 - 0.305% Li (Atacama); 10 - 47 ppm (geothermal)	N/A (brine source)	~1% (all Li)	No	Residual brines, sludge, saturated resins; water consumption in arid regions	DLE/DLE-R technologies; closed-loop water circuits	Solid waste from metal hydroxide precipitation (up to 5,000 mg/kg brine); local impacts disproportionate to share
Phosphate sedimentary deposits	10 - 30% P ₂ O ₅	~10 ¹	~4%	No	Phosphogypsum waste; potential radioactivity (NORM)	Agricultural soil amendment; gypsum by-product	Geochemical characterization required; radioactive content varies by deposit
Medium Potential							
High-grade iron ores (hematite)	>60% Fe	~9 (iron global avg.)	~9% (all iron)	No	Residual ultrafine particles; market absorption of fines	Pellet feed; industrial sand; construction materials	Market saturation for by-products; competition with building material producers
Low-grade iron ores (itabirite)	<45% Fe	~15-100	(incl. in iron 9%)	No	Very large volumes of ultrafine tailings; costly dewatering	Filtered tailings stacking; high-frequency screens; pressure filtration	Silica/iron fines face limited market; filtration reduces water, not volume
Flake graphite	High-carbon deposits	Data limited	<1%	No	Contamination variability; processing residues	Mineral fillers; cementitious binders; construction materials	Market development needed for filler applications
Lithium from hard rock (pegmatite)	1~2% Li ₂ O (theoretical 7.9%)	~1,600 (hard-rock avg.)	(incl. in Li ~1%)	No	~350,000 t/yr waste per 11,000 t Li ₂ CO ₃ ; finely ground tailings + waste rock	Ceramics; construction materials; fertilizer from waste rock	Waste rock disposal is still required; scale mismatch between tailings volume and by-product markets
Low Potential							
Nickel-cobalt deposits (laterite and sulfide)	0.8-1.5% Ni (laterite); 1-3% Ni (sulfide)	~250 (Ni avg.); ~859 (Co avg.)	<3%	Partial	Iron-rich slurries, acidic residues (HPAL); chemically reactive tailings (sulfide); secure containment needed	Multi-element recovery; by-product valorization (Fe, Co, Mn)	Chemical complexity of residues; stabilization technology immature; limited by-product markets
Complex zinc ores	Typically, low grade	~71 (Zn global avg.)	~3% (Pb-Zn)	Yes	Lotation inefficiency with carbonate gangue; fines contamination; AMD risk	improved mineral separation; by-product recovery (In, Ga, Ge)	Separation breakthroughs required; by-product recovery infrastructure concentrated in China
Very Low Potential							
Copper deposits	0.5-2% Cu	~510 (global avg.); range 2-17,000	46%	Yes	90-98% of ore becomes tailings; AMD; arsenic; flotation reagents; occasionally radioactive	Re-mining (e.g., MVC/EI Teniente); hydrometallurgy; in-pit backfill; pyrite-to-sulfuric acid	Sheer volume (8 Bt/yr); chemical reactivity precludes most reuse; even advanced operations produce hazardous waste

Table 1: Classification of mineral types by tailings reduction potential.



ESG commitments or corporate practices, which may significantly affect implementation. A deposit with high technical potential may still generate substantial tailings if operational strategies do not prioritize reduction.

Deposits that are most compatible with tailings reduction strategies typically exhibit three concurrent conditions. Firstly, they produce chemically inert residues, which pose minimal environmental risk and simplify disposal or reuse. Secondly, the tailings generated can be repurposed as industrial byproducts, such as construction materials, mineral fillers, or agricultural amendments. Thirdly, these deposits allow for the implementation of integrated or closed-loop processing circuits, where material losses are minimal and residues can be efficiently recovered or reintegrated into the production cycle. These characteristics significantly enhance the technical and economic feasibility to potentially achieve tailings reduction or elimination, enabling mining operations to transition from waste management to resource optimization.

The scale of the tailings challenge varies enormously across mineral commodities. Nassar et al. (2022) calculated rock-to-metal ratios (RMRs) – the total mass of ore mined and waste rock removed per unit of refined metal – for 25 commodities and found they span eight orders of magnitude, from roughly 10 tons per ton of metal for iron and aluminum to over 1 million tons per ton for gold and platinum group metals. Copper, gold, and iron ore together account for 83% of all material displaced by mining globally. These ratios set the physical boundaries of what tailings reduction can realistically achieve for each commodity: a mineral with an RMR of 500 faces a fundamentally different reduction challenge than one with an RMR of 10. The classification in Table 1 below should be read in this context.

High potential deposits typically satisfy all three conditions: their residues are chemically inert, their tailings have established or emerging reuse pathways, and their processing routes are amenable to closed-loop or near-closed-loop circuits.

- **Rare earths from placer deposits:** as demonstrated by the Moma and Richards Bay Minerals operations (Section 5.3.2), alluvial and beach sand deposits generate tailings that are relatively easy to reintegrate into the environment. However, larger-scale projects may require tailings storage facilities (TSFs), resulting in tailings profiles ranging from low to conventional depending on operational scale. Idiosyncratic characteristics of monazite placer deposits, such as trace radioactive elements, may render these more difficult to store or upcycle.
- **Crushed stone and aggregates:** although chemically inert and typically devoid of valuable content, they can have viable economic destinations, particularly in the construction

industry. However, their reuse faces market resistance due to issues with quality specifications, logistics, and perception.

- **Lithium from brines** as examined in Section 5.3.2, emerging DLE technologies substantially reduce water use and enable ultra-low to low tailings operations. However, residual brines, saturated resins or adsorbents, and sludge remain unavoidable.
- **Phosphate Sedimentary Deposits:** these typically contain between 10% and 30% phosphorus pentoxide (P_2O_5), producing tailings with distinct characteristics and high potential for beneficial reuse. These tailings may be directly applied to agricultural soils due to their residual nutrient content or converted into valuable byproducts such as agricultural gypsum. However, the viability of these applications depends on thorough geochemical characterization and environmental risk assessment to ensure both safety and agronomic effectiveness

Medium-potential deposits typically meet one or two of the qualifying conditions but not all: their tailings are often inert and technically suitable for reuse, yet limited market absorption capacity keeps the loop from fully closing. This constraint is sharpest in construction, where the volume of reusable mine waste dwarfs what building-material markets can absorb. Pushing that material into the market at scale would depress prices and erode the competitiveness of established producers, and the resulting glut could drive smaller, less resilient firms out entirely. Reusability, in short, is necessary but not sufficient for circularity: absent durable demand, even an inert, reuse-ready tailings stream has nowhere to go. Medium-potential deposit types include:

- **High-grade iron ores (hematite):** especially compact hematite with Fe content exceeding 60%, exhibit simple mineralogy makeups that allow for recovery rates above 90%. Residual fines can be repurposed as pellet feed or industrial sand, further contributing to waste minimization.
- **Low-grade iron ores (itabirite):** Low-grade itabirite ores generate large volumes of ultrafine tailings, requiring costly dewatering and filtration. While filtered tailings stacking is technically feasible and reduces tailings volume, it does not eliminate or provide a definitive destination. Additionally, byproducts such as silica and iron-rich fines face limited market absorption, restricting valorization potential. These economic and logistical constraints make full tailings elimination unlikely, though gradual optimization using high-frequency screens and pressure filtration offer reduction pathways.
- **Flake graphite:** when found in high-carbon deposits with minimal contamination, they can



achieve recovery rates exceeding 80%, with inert tailings suitable for use as mineral fillers. These tailings may also have economic uses, particularly in construction materials, cementitious binders, and industrial fillers.

- **Lithium from hard rock (pegmatite):** typically contains 1–2% Li_2O and requires flotation and calcination. Although operations generate large volumes of finely ground tailings and blasted waste rock, these residues may have economic destinations, particularly in ceramics and construction materials. However, some projects have still shown the need for waste rock disposal despite the upcycling potential.

For low potential deposits, none of the three conditions is fully met: residues are often chemically reactive, reuse pathways are limited or unproven, and processing complexity rules out closed-loop operation. In most instances, the volume of tailings far exceeds the mass of the saleable product – at times more than 90% of the total ore processed (Kossoff et al., 2014). For deposits like these the operational objective necessarily shifts from eliminating tailings to minimizing their risks and long-term impacts, and responsible tailings management becomes essential precisely where reduction or elimination is not technically attainable. Among the most challenging examples are:

- **Nickel-cobalt deposits:** Whether laterite ores are treated by high-pressure acid leaching (HPAL) for laterite ores or sulfide ores by other hydrometallurgical routes, nickel-cobalt operations generate chemically reactive tailings – iron-rich slurries, acidic residues, or both – that require secure containment. Multi-element recovery and by-product valorization can reduce volumes, but the chemical complexity of these waste streams renders complete elimination unlikely absent significant advances in residue stabilization.
- **Complex zinc ores:** Ores such as sphalerite in carbonate gangue are typically low-grade and difficult to liberate, producing flotation inefficiencies and fines contamination. The result is substantial tailings generation with limited reuse potential, which makes large-scale tailings reduction initiatives impractical without breakthroughs in mineral separation.

Very low potential deposits actively violate the first condition: their tailings are chemically hazardous, radioactive, or both, so reuse is infeasible and strict, and long-term containment is mandatory. Residues from these ores cannot be reused and must be disposed-of and monitored to ensure the stability of their tailings storage facilities (TSFs). This group includes:

- **Copper deposits:** Copper sulfides concentrate efficiently, and the metal's high value supports advanced processing – clean hydrometallurgical

techniques, selective mining, and filter cakes that recover residual values – so volumetric tailings reduction is often achievable. What keeps copper in this category is not volume but residual hazard: even in technologically advanced operations, the tailings can carry leftover copper, toxic elements (notably arsenic), flotation reagents, acids, and occasionally radioactive constituents, leaving them chemically reactive and environmentally hazardous and dependent on secure containment.

- **High-grade underground gold deposits:** These favor selective mining and efficient recovery, with minimal dilution and a high concentration of valuable material, and gold's high value justifies advanced extraction and processing – gravity separation, intensive leaching, and sensor-based ore sorting – that markedly reduces tailings generation. Even so, the tailings can contain residual gold, sulfides, cyanide compounds, and other process reagents whose toxicity and chemical reactivity pose environmental and safety risks, requiring robust management and treatment.
- **Gold ores associated with sulfides (low-grade):** Here the gold is locked within sulfide minerals such as pyrite and arsenopyrite and is largely inaccessible to direct cyanidation, so an oxidative pretreatment step – roasting, pressure oxidation, or bio-oxidation – is required to liberate it. That pretreatment is itself a principal source of hazard: the resulting tailings can carry arsenic, residual cyanide, and other toxic, persistent compounds that demand secure disposal, and whose toxicity is a major barrier to tailings elimination.
- **Rare earth elements from alkaline rocks:** Here the gold is locked within sulfide minerals such as pyrite and arsenopyrite and is largely inaccessible to direct cyanidation, so an oxidative pretreatment step – roasting, pressure oxidation, or bio-oxidation – is required to liberate it. That pretreatment is itself a principal source of hazard: the resulting tailings can carry arsenic, residual cyanide, and other toxic, persistent compounds that demand secure disposal, and whose toxicity is a major barrier to tailings elimination.

To achieve higher rates of tailings reduction, stakeholders, especially mining companies, must recognize that this goal cannot be determined solely by mineralogical or metallurgical factors. It should be approached as a systematic objective, integrating technological, environmental, and organizational dimensions. This framework (Figure 7 and Figure 8) aims to assist with strategic planning and help to identify opportunities for innovation in tailings management across different mineral systems.



Figure 7: Minerals Potential in relation to "Zero Tailings".

Tailings Reduction or Elimination Feasibility by Deposit Type

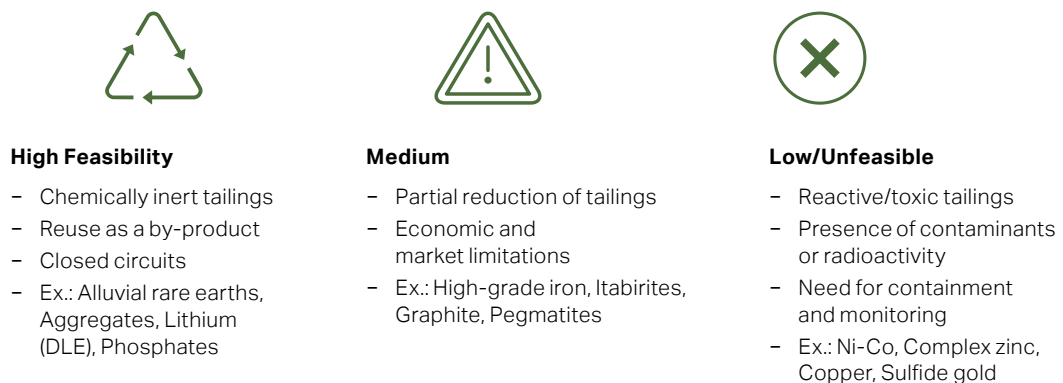


Figure 8: Summary of mineral feasibility for tailings reduction or elimination.



Engineering Zero Tailings

06



6. Engineering Tailings Reduction

In practice, current tailings reduction initiatives can be categorized into four main classes:

- **High utilization of extracted material:** Through the integration of geological, technological, and economic factors, it is possible to pursue the goal of economically utilizing all minerals present in the deposit, including those considered secondary or of lower commercial value. This approach is most feasible in deposits with simple mineralogy, high grades, and compatibility with dry processing or closed-loop water circuits, typically at small to medium scale. Where these conditions are met, “near-zero tailings” outcomes are technically achievable.
- **Reuse of tailings for alternative applications:** This approach involves redirecting tailings generated during mineral processing to other production chains, transforming them into inputs for sectors such as cement manufacturing, paving, ceramics, abrasives, fertilizers, and industrial acids. In the cement sector, for example, tailings can replace part of the clinker, while in paving and ceramics they can serve as aggregates. In fertilizers, minerals such as iron and manganese oxides can enrich agricultural formulations. By displacing the extraction of natural raw materials in these production chains, tailings reuse promotes circular economy principles while creating new economic opportunities. However, this reuse typically occurs only partially due to the mismatch between the extraction rate of the primary mineral and the demand for by-products, maintaining the need for geotechnical structures to ensure safe disposal of the remainder.
- **Reprocessing of legacy tailings deposits:** Legacy tailings may contain significant concentrations of metals or minerals that were not previously extracted due to technological or economic limitations at the time of original processing. By improving beneficiation processes or capitalizing on the increased market value of residual minerals, historical tailings deposits can be reprocessed using techniques such as flotation, leaching, magnetic separation, and bioleaching, transforming waste into secondary sources of raw materials. This practice can add economic value while reducing environmental liabilities and decreasing the volume of stored tailings. However, risks and liabilities from reprocessed tailings facilities still exist, and the process may require the creation of new disposal areas.

- **Improvement of tailings disposal methods and locations:** This class encompasses two primary strategies. Filtration techniques, using filter presses or disc filters to reduce tailings moisture content until the material reaches a consistency similar to damp soil, enable tailings to be transported and disposed of in compacted stacks, eliminating the need for conventional containment dams. This approach offers reduced risk of dam failure, increased water recovery, and a smaller footprint for tailings deposition. However, filtration processes can be energy-intensive, particularly when dealing with ultra-fine tailings or large volumes of material, and the energy demand associated with high-pressure filtration equipment and transporting filtered tailings must be carefully evaluated. Backfilling, the second strategy, involves filling cavities created by mining operations with materials derived from tailings or waste rock, which can be mixed with binders such as cement to ensure stability. Widely used in underground mines and, in some cases, in open-pit mines, backfilling improves structural safety, reduces subsidence, minimizes environmental impacts, and optimizes internal mine space utilization. While neither approach eliminates tailings generation, they reconfigure how tailings are stored and managed, contributing to lowering the environmental and geotechnical risks associated with conventional tailings storage.

The achievability of these approaches varies by deposit type, geological formation, and economic context. In specific cases that combine advanced technologies with favorable mineral deposits – characterized by higher homogeneity and grade, as well as small to medium-scale operations – the full utilization of extracted ore without tailings generation is technically feasible and economically viable. For most operations, however, the initiatives that are currently achievable tend to involve a mix of partial reuse, impact containment, and risk reduction rather than complete tailings elimination. As discussed in Section 3, these approaches carry their own environmental and social trade-offs that must be assessed with equal rigor.

Additionally, heap leaching warrants mention in any survey of tailings management, though it sits awkwardly within that frame. It is not a tailings strategy but an alternative extraction method: crushed ore is stacked on lined pads and percolated with lixiviants (e.g. cyanide for gold and silver, sulfuric acid for copper and uranium) to dissolve and recover target metals. In that narrow sense, it represents a meaningful advance. But heap leaching is neither representative nor generalizable: it is viable only for specific ore types and metallurgies, and it introduces its own liabilities – leach pad liner integrity, pregnant leach solution management, long-term cyanide or acid drainage, and the long-term permanent



footprint liabilities and stability challenges of spent heaps. It is best understood not as a model for the industry’s tailings problem, but as a niche case in which the extractive route happens to sidestep slurry tailings while creating a different category of waste landform.

The technical and environmental feasibility of tailings reduction initiatives is discussed in the following sections of this chapter. The technologies studied or currently being applied are presented and categorized by benefits and limitations (Table 2).

Technological Solution	Benefits	Limitations / Risks
High Utilization of Extracted Material	Elimination of tailings; greater resource efficiency; reduction of liabilities	Feasible only in simple, small-scale deposits; requires market demand for all products.
Tailings reuse	Reduced disposal volumes; generation of by-products; promotion of the circular economy	Partial reuse; dependence on local markets; requires technical validation.
Reprocessing of legacy tailings	Recovery of residual metals; reduction of historical liabilities; avoids new mining	It may generate new tailings, environmental risks, and high operational costs.
Dewatered Tailings Stacking	Enhanced geotechnical safety; water recovery; avoids tailings dams	High energy consumption, potential instability, and an elevated carbon footprint.
Backfilling of pits/mines	Environmental rehabilitation; geotechnical stability; reduced impacted areas	Tailings must be chemically stable; the costs associated with cement and transportation.
Heap Leach	Elimination of conventional tailings and dam structures; lower water use (no flotation or pumped transport for disposal); lower energy intensity via reduced crushing and grinding; unlocks production on site of difficult process ores or those with imposed smelter fines (e.g. arsenic-bearing copper ores).	Long-term geotechnical instability risks of heap leach facilities, especially active ones (notable failures in Canada, USA, Turkey); potential acid mine drainage into groundwater or surface water; permanent environmental legacy of “spent ore” stacks that continue to leach if not properly capped.

Table 2: Trade-offs of tailings reduction and elimination solutions.



6.1 High Utilization of Extracted Material

The complete elimination of waste or the full utilization of extracted ore is only technically feasible and economically viable under specific geological, technological, economic, and regulatory conditions. Mineral deposits that enable the full utilization of extracted material share a distinct set of geological and technical characteristics that make them compatible with tailings-free processing approaches. Typically, these deposits exhibit simple and homogeneous mineralogy, where the target minerals are easily liberated and the gangue consists of inert or commercially viable materials such as quartz, carbonates, and certain clays. They often present high ore grades and minimal mineral intergrowth, which facilitates efficient separation and recovery.

From a hydrogeological standpoint, such deposits pose low environmental risk, as they do not generate acid mine drainage or mobilize toxic elements. Technologically, they allow dry processing routes or closed-loop water circuits, which eliminate the generation of tailings slurries and liquid effluents that, if stored in large dam structures, can be geotechnically unstable. Additionally, these deposits are usually associated with small to medium-scale operations, where process control and material handling can be optimized to achieve near-complete resource utilization.

The economic feasibility of full ore utilization is based on the existence of markets for these materials and on an operational scale that is typically compatible with small-to medium-sized enterprises. There are some practical examples of the extraction of certain minerals, combined with a set of favorable characteristics that allow near to full utilization without or with minimum

tailings generation. Theoretically, these projects may achieve optimal conditions that allow “Near-Zero Tailings” results. They are listed below:

- **Potassium:** Through the integration of mining and industrial chemical processes, glauconitic siltstone reserves enable the complete utilization of the extracted rock, allowing for its transformation into various commercial products, including potassium sulfate, aluminum oxide, iron oxides, magnesium sulfate, and potassium feldspar. According to the operator, as described in “Projeto Glauconita” presentation (Kalium Mineração, n.d.) the unique geological and operational conditions create a scenario in which the material to be mined contains no overburden, requires no waste disposal, and does not demand physical or chemical beneficiation processes, meaning zero water consumption and zero chemical reagents. Mining is carried out entirely through a dry extraction process, eliminating the need for tailings dams. However, no publicly available information was found that discloses these results.
- **Bauxite:** In high-quality lateritic bauxite deposits, fully dry beneficiation is technically feasible. This process yields two main products: metallurgical-grade bauxite, used in the aluminum industry, and industrial-grade bauxite, applied in refractories, abrasives, ceramics, and cement, ensuring the full utilization of all particle size fractions as either a product or a co-product. However, according to Terra Goyana (2022), a reduced volume of low-grade ore (anorthosite and high-iron / high-CaO fractions) is generated and disposed of in fewer waste piles. This material can indeed be considered tailings, or at a minimum, mining waste.



6.2 Reuse of Tailings for Alternative Applications

The reuse of mineral tailings by other industries represents a strategic alternative for reducing environmental impacts and improving resource efficiency. However, this reuse typically occurs only partially due to the mismatch between the extraction rate of the primary mineral, driven by market and operational factors, and the demand for byproducts contained in the tailings. Although these initiatives are technically feasible and environmentally desirable, the absorption capacity of local and regional markets remains limited. This constraint prevents the full utilization of tailings, maintaining the need for geotechnical structures to ensure safe disposal.

Practical examples of potential tailings re-use by mineral type for other industries:

- **Zinc:** Tailings from zinc mining can be partially reused in various applications. Notable initiatives include the use of flotation residues as soil acidity correctives, the production of iron concentrate through magnetic separation, and the use of gypsum-rich sludge as a substitute for natural gypsum in cement manufacturing (Nexa Resources, 2024). Additional applications under evaluation include the use of goethite in brick and precast production, as well as jarosite as a pigment and additive in concrete blocks. Other research fronts explore the use of silica- and calcite-rich tailings as supplementary cementitious materials, as well as the development of high-purity pyrite concentrates (Liu et al., 2017). Critical minerals, such as germanium, are also enriched in zinc tailings and byproduct streams. Globally, only a small fraction of germanium contained in zinc concentrates – less than 5 percent – reaches refineries equipped to extract and produce germanium, and recovery rates may be as low as 3 percent (Patel & Karamalidis, 2021). Most zinc concentrates produced at the Alaskan Red Dog mine are shipped to Teck Resources' facilities in British Columbia, Canada, where germanium is separated and refined (Baskaran & Schwartz, 2025). One notable initiative is led by Nyrstar, which has announced a \$150 million investment to expand its zinc operations in Tennessee and add gallium and germanium processing capabilities (Williams, 2022; Baskaran & Schwartz, 2025). While these solutions are promising, they still require technical validation and economic feasibility assessments before being scaled up for industrial use.
- **Iron:** Tailings generated from iron ore mining have been partially reused in several areas, primarily focused on creating byproducts (Vale S.A., n.d.; Vale S.A., 2020). Key initiatives include

the production of industrial sand for use in construction and the manufacturing of precast blocks from tailings. Additional applications include the use of iron and manganese oxides from tailings to enrich agricultural fertilizer formulations. While such initiatives represent important steps toward a circular economy, their scale remains limited compared to the total volume of waste generated, and their replicability depends on economic viability and market demand for the byproducts.

- **Nickel, Copper, and Cobalt:** Tailings from nickel, copper, and cobalt mining have been the subject of pilot testing using bacterial bioleaching technologies, which aim to recover valuable metals through the use of microorganisms in controlled environments (Neale, 2020). This approach seeks to transform tailings into marketable byproducts or inert materials, with notable developments including the recovery of iron as magnetite, the conversion of sulfuric acid into fertilizer (ammonium sulfate), and the reuse of silicates in civil applications or as mine backfill material. The water used in the process is recirculated in a closed-loop system, reducing effluent generation. Despite its environmental and technological potential, this initiative remains in the operational testing and technical validation phase, facing challenges such as material variability, high costs, and the need for specialized infrastructure.
- **Graphite:** Graphite tailings reduction has been explored through the transformation of downstream industrial wastes into inputs for other production chains. Key initiatives include the recycling of graphite from used batteries and industrial residues to produce high-performance anodes, as well as the development of graphitic and graphene-based additives for use in construction materials such as concrete and coatings (Talga Group, 2025). Although these initiatives do not constitute typical tailings reduction solutions, they contribute to reducing the demand for new extraction fronts and offer alternative pathways for managing industrial waste.

These solutions currently operate on a limited scale and require further technical validation, industrial scalability, and the consolidation of consumer markets to ensure long-term economic viability. The valorization of materials beyond the primary ore should be understood not as peripheral, but as a central component of a comprehensive tailings reduction strategy.

6.3 Reprocessing Legacy Tailings Deposits

The reprocessing of legacy tailings deposits, such as dams and dewatered tailings piles, can become both technically viable and economically attractive when compared to the development of new mining operations. In some cases, the metal content in these deposits exceeds that of natural ore bodies due to a combination of higher grades of the source deposit and older, less efficient processing technologies at the time the tailings were generated. Reprocessing may also target secondary minerals, as seen in the recovery of gold from historical copper and iron tailings deposits.

Furthermore, emerging technologies, such as bioleaching, flotation with highly selective reagents, and selective hydrometallurgy, are enabling the extraction of minerals that were previously unrecoverable. For example, Godirilwe et al. (2021) demonstrated that high-pressure leaching combined with solvent extraction-electrowinning (SX-EW) can recover copper from mine tailings while reducing environmental loading. Another factor driving reprocessing is the increase in market value of certain minerals, which justifies greater investment in advanced beneficiation technologies.

In these cases, there is an ecological advantage in avoiding the opening of new mining fronts. However, the process may require the creation of new disposal areas. It can involve environmental and geotechnical risks, particularly in leaching and bioleaching operations that require saturation of stacked heaps with chemical reagents and/or biological agents.

Practical examples of legacy tailings reprocessing by mineral type:

- **Iron:** The reprocessing of tailings in iron ore mining has been adopted as a strategy to transform previously discarded materials into productive inputs. This approach involves the extraction and reprocessing of legacy tailings stored in containment structures, as well as the recovery of tailings generated during the decommissioning process of the dam. The recovered materials undergo concentration stages, such as magnetic separation, to produce high-grade iron products used in pelletizing chains or sold commercially. However, their implementation remains limited in scale and depends on technical feasibility, metal content of the tailings, and market demand for the resulting products.
- **Gold:** The reprocessing of gold tailings through heap leaching enables the extraction of residual metal from previously processed materials. However, this method presents significant environmental and geotechnical risks. Among the most critical are the potential for static liquefaction of saturated material, slope failures due to inadequate drainage, soil and water contamination from chemical solutions such as cyanide, and physical instability of the heaps. These risks demand rigorous control in design, operation and monitoring, as failures can lead to collapses with severe environmental consequences.

Earthworks commissioned research into the opportunities and risks of re-mining tailings, in which it states that the reprocessing of tailings offers a valuable opportunity for the mining sector both to recover resources and to reduce historical environmental liabilities, while also contributing to circular economy practices. However, its success depends on aligning technological feasibility, market conditions, and robust risk management to ensure safe and responsible outcomes (Maest, 2023).





6.4 Improvement of Tailings Disposal Methods and Locations

Some mining companies have been actively pursuing disposal solutions that reduce structural risks and minimize environmental and social impacts. These efforts align with evolving expectations from regulators, investors and communities. Among the adopted solutions, underground mine and pit backfilling, as well as dewatered tailings piles, stand out. These methods are designed to reduce geotechnical risks and limit environmental exposure. However, while dewatered tailings piles are generally considered lower risk than conventional slurry-based dams, they may still pose significant environmental and geotechnical risks if poorly designed, constructed, or managed.

Backfilling of abandoned mines is a traditional practice in the mining industry, particularly during the closure stages, which contributes to environmental rehabilitation of mined areas and geotechnical stability, including the reduction of surface subsidence risk. Dewatered tailings piles, while not new, have been adopted on an industrial scale following updates to global standards for tailings safety and management. This method offers geotechnical advantages, including improved stability control and reduced risk of catastrophic failure. However, its environmental impacts are still under investigation, and there is insufficient evidence to claim that dewatered tailings piles are environmentally superior to other disposal methods in all contexts.

The technical and economic feasibility of these solutions has been demonstrated in operations involving a wide range of minerals. The following examples illustrate how backfilling and dewatered tailings piles have been applied in different mineral contexts:

- **Iron:** Dewatered tailings piles have been increasingly adopted in iron ore operations, particularly by filtration and large-scale drained stacking as an alternative to conventional tailings dams. When implemented in accordance with industry standards and best practices, this method not only reduces geotechnical risks but also enables the reuse of tailings as raw materials for the construction industry, such as industrial sand and concrete blocks. Vale's Capanema mine in Minas Gerais, inaugurated in 2025 with a R\$67 billion investment, exemplifies the natural-moisture (filtered) tailings approach (Vale S.A., 2025).
- **Copper:** In copper mining, dewatered tailings piles have been tested in water-scarce regions, while backfilling is commonly applied in underground mines. In this method, tailings are mixed with

cement and used to fill mined-out stopes, enhancing operational safety and ground stability.

- **Gold:** Given that gold mining operations typically process large volumes of ore due to the low grade of most deposits, gold mining operations have also adopted dewatered tailings piles as an alternative to traditional tailings dams, aiming to reduce environmental and safety risks associated with dam failure. In gold operations involving cyanide leaching, the risk of environmental contamination remains if chemical treatment and containment systems are not adequately implemented. Studies in Life Cycle Assessment (LCA) suggest that dewatered tailings piles may lead to a higher carbon footprint compared to conventional disposal methods, particularly when road transportation and energy-intensive filtration systems are involved (Wang et al., 2022).
- **Lithium:** In pegmatite-hosted lithium deposits, igneous rocks characterized by extremely coarse grains make dewatered tailings piles possible through technologies such as dense media separation (DMS). This process produces dry tailings with high purity, which are stacked in drained structures and, in some cases, marketed as inputs for other industrial sectors.
- **Cobalt:** Although cobalt is typically extracted as a co-product of copper or nickel mining, pilot projects have explored the combined use of backfilling and dewatered tailings piles, along with biotechnologies, to convert tailings into inert or marketable materials (Shengo Lutandula & Maloba, 2013). While still in the testing phase, these approaches represent promising alternatives for sustainable tailings management.
- **Bauxite:** In bauxite mining, dewatered tailings piles have been successfully implemented by relocating dry tailings into exhausted pits, replacing the need for tailings dams. Thickened backfill of caves is also a demonstrated technique for managing bauxite tailings, whereby the tailings are increased in solids content to near-paste consistency in order to be placed in a controlled, stable manner. This practice benefits topographic restoration and facilitates environmental rehabilitation.
- **Zinc:** Zinc operations have combined dewatered tailings piles with backfilling techniques. A portion of the tailings is mixed with cement and used to fill underground voids, while the remainder is placed in dewatered tailings piles on the surface.
- **Titanium:** In ilmenite deposits, dewatered tailings piles are being studied as a strategy to reduce environmental impacts. The tailings, primarily composed of quartz sand, are stacked in drained



structures and in some cases reused in civil construction or land reclamation projects.

- **Graphite:** In graphite mining, backfilling has been employed to fill open pits with waste rock or drained tailings, followed by capping and revegetation to support post-mining land use and ecological restoration.

Dewatered tailings piles are associated with multiple mining operations and offer important environmental and social benefits, including improved geotechnical safety and enhanced water recovery, especially in

regions facing water scarcity or high environmental sensitivity. However, it is essential to recognize that these solutions do not eliminate tailings generation; they merely reshape the way tailings are stored and managed, shifting the focus from containment to long-term stability and environmental integration. While dewatered tailings piles may demonstrate meaningful progress in tailings management, they should not be misrepresented as a tailings elimination solution.

	Backfilling	Dewatered Tailings Stacks (Dry / Dewatered Stacking)	Combined Method (Backfilling + Dewatered Stacks)	Conventional Dam / Strict Containment
Key criteria	<ul style="list-style-type: none"> - Underground or Open-Pit Mines, Exhausted or in the Process of Closure - Fine or paste tailings - Need for geotechnical stability 	<ul style="list-style-type: none"> - Possibility of filtration or dry separation - Reduced risk of failure - High water recovery 	<ul style="list-style-type: none"> - Part of the tailings used structurally - Remainder disposed in drained stacks - Optimization of safety and volume 	<ul style="list-style-type: none"> - Chemically reactive tailings - Presence of contaminants or radioactivity - High chemical complexity
Typical minerals	<ul style="list-style-type: none"> - Copper (underground mines cemented tailings) - Underground gold (high grade) - Zinc (part of the tailings) - Graphite (exhausted pits and wells) - Cobalt (in pilot projects) 	<ul style="list-style-type: none"> - Iron - Gold - Lithium (pegmatites – DMS) - Bauxite - Titanium (ilmenite) - Copper (areas with water scarcity) 	<ul style="list-style-type: none"> - Zinc - Copper - Cobalt - Some gold operations 	<ul style="list-style-type: none"> - Nickel-cobalt (HPAL) - Gold with cyanidation and sulfides - Complex zinc - Rare earths with radionuclides - Copper with reagent tailings

Table 3: Summary of most common initiatives applicable to mineral type.

6.5 Tailings Reduction Technologies

A useful organizing framework is provided by the International Council on Mining and Metals' Tailings Reduction Roadmap (ICMM, 2022), which maps tailings reduction technologies onto intervention points along the mining value chain. Upstream interventions, preventing or reducing waste at the source, deliver greater impact than downstream ones such as recycling, recovery, or containment. For mining companies to start implementing tailings reduction at scale, it is most favorable to them financially to start doing this as early in the mining process as possible to reduce OPEX of drilling, blasting, hauling, crushing, grinding and floating more material.

Based on these findings, this report refines the technology themes identified in the Tailings Reduction Roadmap with the highest potential impact on tailings reduction:

- **Advanced geo-metallurgy:** Deep and detailed ore-body characterization using advanced spectroscopic tools, radar, and remote sensing.
- **Advanced particle sensing:** Minimization or elimination of waste-rock production using geo-metallurgical characterization methods (e.g. XRD) applied at the mine face via shovels, diggers or equivalent.
- **Bulk ore sorting:** Application of penetrative sensors to large ore volumes to improve process circuit efficiency for optimal mineral liberation, recovery, and waste accounting.
- **In-situ extraction:** Extraction of minerals via chemical leaching, which still produces waste rock, but requires less water and energy than traditional concentration techniques; however, this introduces its own suite of geotechnical stability and pollution complications different from tailings, but beyond the scope of this report.
- **Preferential fracturing:** Controlled breakage at mineral grain boundaries or larger geologic contacts.

Crucially, ICMM's landscape assessment concluded that no single technology can be deployed at scale across the industry. Tailings compositional variability, integration challenges with existing processes, and site-specific characteristics mean that operators must conduct site-by-site assessments to identify the most suitable reduction, valorization, or enhancement pathway. This finding underscores a broader systemic issue: industry has failed to integrate holistic approaches capable of disrupting entrenched processes.



**Economic Impact of Implementing Tailings
Reduction Technologies in Mining Operations**

07



7. Economic Impact of Implementing Tailings Reduction Technologies in Mining Operations

The transition to a model in mining which emphasizes tailings reduction would be more than a technological shift; it would mean a profound transformation in the economic logic of mineral operations on a global scale. Although environmentally desirable, it would pose significant financial challenges, particularly in terms of operational expenditures (OPEX).

The feasibility of achieving higher rates of tailings reduction is determined by a comprehensive cost-benefit analysis that considers both short- and long-term implications. Initial capital expenditure (CAPEX) for implementing advanced processing technologies and infrastructure is often substantial, while operating costs (OPEX) associated with energy consumption, water management, and specialized treatment can significantly impact profitability.

In the initial phases, implementing solutions that eliminate or entirely repurpose tailings tends to increase direct costs. This is primarily due to the greater complexity of processing circuits, which require specialized equipment such as filter presses, centrifuges, leaching reactors, and drying systems,

resulting in higher energy and chemical reagent consumption. Moreover, the production of marketable by-products requires stricter quality control standards and a more technically skilled workforce. Combined, these factors result in a cost per ton processed that exceeds that of conventional operations.

On the other hand, the indirect benefits of adopting a tailings reduction strategy can be substantial and may offset initial investments over time. The elimination of tailings storage facilities (TSFs), for example, significantly reduces expenditures related to construction, maintenance, and monitoring. It also lowers long-term environmental liabilities and the costs associated with mine closure and rehabilitation of degraded areas. As a result of catastrophic tailings dam failures in multiple countries, such as those in Brazil, Canada, and South Africa, reducing legal and reputational risks has become a strategic priority. Additionally, streamlined permitting processes and the strengthening of integrative approaches, such as the social license to operate, contribute to greater project stability and continuity. Reprocessing existing tailings can also extend the productive life of existing mine sites, deferring the need to develop new deposits and providing additional revenue to fund responsible closure. By integrating advanced recovery and beneficiation technologies, it is possible to mitigate some socio-environmental impacts, streamline licensing processes, increase social approval, and promote a mining model aligned with sustainability principles (Brito et al., 2024).

Another relevant benefit lies in the potential to generate new revenue streams. Operations aligned with the tailings reduction concept can commercialize by-





products such as clays, silica, iron-rich residues, and materials for the construction industry. These products, derived from tailings, may find demand in various sectors, including the cement, ceramics, agricultural, and refractory industries. Furthermore, companies may benefit from environmental credits, improved ESG ratings, and access to green financing instruments, such as green bonds and sustainability-linked loans.

Market demand for secondary products derived from tailings can play a critical role in offsetting the costs to implement tailings reduction initiatives, as successful commercialization transforms waste into revenue streams. However, uncertainties related to market volatility, pricing and logistical constraints introduce commercial risks that must be carefully managed. Economic incentives, such as tax benefits or subsidies, and supportive regulatory frameworks can mitigate these challenges and accelerate the adoption of tailings reduction strategies, but their effectiveness depends on regional policies and industry collaboration. The commercialization of co-products or byproducts derived from tailings, such as sustainable sand produced from iron ore, although representing strategic reuse alternatives, may introduce new socio-economic impacts in municipalities with already well-established supply chains. The success of these initiatives depends on the existence of a market willing to adopt such

products, and there is a risk of unfair competition due to the large production capacity, logistical infrastructure, and financial resources of major mining companies.

It is essential to note that the economic impact of adopting higher rates of tailings reduction varies depending on the deposit type, project scale, and proximity to industrial markets. Projects with long life spans, robust infrastructure, and integration with downstream industries tend to exhibit greater economic viability.

The relative differences in key operational cost (OPEX) components between conventional mining models and an operation targeting tailings reduction vary depending on the criteria analyzed. An exploratory exercise illustrating these differences is presented in Table 4.

In summary, tailings reduction initiatives should not be viewed merely as a technical proposal, but as a structural transformation in the economic structure of mining. Despite involving higher short-term costs, its environmental, social, regulatory, and reputational benefits point toward a more resilient and sustainable mining industry, aligned with the global demands of the 21st century.

OPEX by Specific Area	Conventional	Toward Zero Tailings	Heap Leach
Power Supply	↓	↑	↓
Reagents	↓	↑	↑
TSF Maintenance	↑	↓	↓
Specialized Labor	↓	↑	↓
Environmental Management	↓	↑	↑
Tailings Transport	↓	↑	↓
Effluent Treatment	↑	↓	↑
Environmental Liabilities	↑	↓	↑

Table 4: Comparison of OPEX components: Conventional vs. "Zero Tailings".



Framework for Evaluating Tailings
Management Approaches

08



8. Framework for Evaluating Tailings Management Approaches

Worldwide, there are examples of mining operations that claim to achieve or approach the concept of “Zero Tailings.” The use of this term, and similar expressions, is relatively common in corporate communications. Despite its innovative appeal, the term lacks a precise technical definition and is sometimes used in a superficial or exaggerated manner

Building on these observations, a wide range of strategies and technologies for tailings reduction and elimination are being developed and implemented

globally, spanning different levels of technical and operational maturity, from early-stage research to industrial-scale applications. These approaches vary in their technological complexity, alignment with circular economy and sustainability principles, associated operational and environmental risks, and the degree of transparency and consistency in how outcomes are reported. To provide a structured understanding of these diverse initiatives, they are organized into a classification matrix.

The matrix positions tailings reduction solutions along two axes: “Main Types of Tailings Reduction” and “Circular Economy Concepts.” This tailings reduction approach, presented on the horizontal axis, is an adaptation of the classification proposed in the Tailings Reduction Roadmap (ICMM, 2022), within the context of discussions held at the MIT Global Summit on Mine Tailings Innovation (MIT Environmental Solutions Initiative, 2024).



Across publicly available information on currently implemented approaches to tailings reduction, a consistent pattern emerges: no operation has achieved complete elimination. All continue to generate residual waste requiring some form of management. The most advanced operations combine multiple strategies (reduce and repurpose) rather than relying on a single approach. The gap between corporate claims and technical reality is persistent: operations described as “Zero Tailings” or “tailings-free” in corporate communications invariably produce waste that must be stored, treated, or monitored. These findings reinforce the need for the graduated performance framework proposed in the following section.

The following framework organizes key tailings reduction initiatives along two complementary axes to support a structured understanding of their interconnections and combined potential. The horizontal axis is defined by the “Reduce / Re-use /

Repurpose” categories, which capture the primary strategies for minimizing waste generation and creating value from by-products.

The concept of “**Reduce**” refers to a set of technological and operational strategies aimed at avoiding or minimizing the volume of tailings generated at the source during mineral production. These approaches focus on improving mineral extraction and processing efficiency, enhancing water recovery, optimizing particle separation, and redirecting tailings for reuse in re-mining or recycling processes, thereby reducing the need for long-term storage. By integrating water management solutions, such as dry processing from the outset and tailings filtration and dewatering, these methods contribute to the increased stability of tailings facilities and reduced socio-environmental risks. The effectiveness of these solutions depends directly on the specific physical and chemical characteristics of the tailings and requires site-specific



investments for adaptation and scaling.

The concept of “**Re-use**” refers to the application of previously generated mining tailings for new purposes within the mining sector itself. This includes the commercialization of tailings for re-mining, the recovery of residual metals through advanced techniques such as bioleaching on legacy deposits, and the use of tailings in environmental rehabilitation and backfilling, where tailings are returned to mined-out areas. Despite their potential, the scalability of tailings re-use is constrained by technical, regulatory, and economic challenges, including geotechnical risks, environmental liabilities, and the need for specialized operational expertise.

The concept of “**Repurpose**” refers to the redirection of previously generated mining tailings for applications in other sectors or production chains, aiming to reduce environmental liabilities and promote resource circularity. This approach involves transforming tailings into co-products/by-products that can be used as raw materials in industries such as construction and manufacturing, where they can serve as aggregates or inputs. By unlocking the economic and functional potential of tailings, repurposing strategies reduce the need for long-term storage and encourage sustainable development across multiple sectors. The feasibility of these solutions depends on the physical and chemical characteristics of the tailings, as well as regulatory, technical, and market conditions.

The vertical axis is informed by core circularity principles, represented here by the concepts of Design for Circularity, Waste and Tailings Valorization, Extension of Useful Life, and Remediation and Restoration. Together. These concepts were based on an article published by the International Geotechnical Center (Centro Geotécnico Internacional [CGI], 2025) titled *Aplicações da economia circular para componentes “menores” em rejeitos de mineração: Uma perspectiva geotécnica, geológica e hidrológica*, which highlights the challenge faced by the global mining industry in meeting rising mineral demand while managing increasing volumes of waste, particularly tailings. It highlights the growing interest in valorizing minor components through strategies aligned with the principles of the circular economy.

The concept of “**Design for Circularity**” refers to the strategic optimization of mining processes to minimize tailings generation from the outset. It focuses on improving mineral extraction and processing efficiency, enhancing selectivity to enable future recovery of byproducts, and selecting inputs that generate fewer residues. This approach also involves integrating low-impact technologies and flexible plant designs. By reducing tailings production and supporting resource efficiency, it facilitates the implementation of circular economy principles throughout the mining value chain.

The concept of “**Waste and Tailings Valorization**” reclassifies tailings and other residues as secondary sources of raw materials rather than mere waste products. This approach involves the recovery of valuable components through chemical or biological extraction, the selective separation of industrial minerals, the recovery of residual metals, and the reclamation of water. By enabling the reintegration of these materials into productive cycles, waste and tailings valorization reduces environmental liabilities and reduces the long-term environmental footprint.

The concept of “**Extension of Useful Life**” refers to the repurposing of processed tailings as inputs for other industrial applications, thereby reducing the volume of waste that requires long-term storage. Examples include the use of tailings in the production of geopolymers, supplementary cementitious materials, soil amendments, construction materials, pigments, and other inputs for external value chains. By reintegrating tailings into productive cycles, this strategy supports collaborative resource utilization across industries while contributing to the implementation of circular economy principles in the mining sector.

The concept of “**Remediation and Restoration**” integrates tailings valorization into mine closure planning, aiming to rehabilitate impacted areas and restore environmental functionality. This approach includes the use of processed tailings for backfilling, the creation of new soil covers, and revegetation, as well as the application of filtration and dewatering technologies to improve tailings characteristics for reuse. By repurposing tailings as inputs for environmental recovery, these strategies enhance land rehabilitation efforts and contribute to the restoration of functions in post-mining landscapes.


The Table 5 summarizes the initiatives related to tailings reduction or elimination in alignment with the previously discussed concepts. Together, these concepts provide an integrated lens through which initiatives can be positioned, articulated, and aligned to advance meaningful progress toward significant tailings reduction or elimination.

The case studies informing the tailings reduction or elimination discussion will be presented in a separate report focused on some project-specific analyses.



	Reduce	Re-use	Repurpose
Design for Circularity	<ul style="list-style-type: none"> - Improvement of mineral processing efficiency; - Improvement of mineral extraction efficiency; - Dry processing from the beginning. 	—	—
Waste and Tailings Valorization	<ul style="list-style-type: none"> - Obtaining minerals through recycling. - Re-mining (reprocessing of tailings). 	<ul style="list-style-type: none"> - Commercialization of tailings for re-mining; - Recovery of residual metals from tailings (including bioleaching). 	—
Extension of Useful Life	—	—	<ul style="list-style-type: none"> - Commercialization of tailings for new functions; - Production of co-products/ subproducts; - Use of tailings as aggregates for civil construction; - Use of tailings in inputs for the transformation industry.
Remediation and Restoration	<ul style="list-style-type: none"> - Filtration and dewatering; 	<ul style="list-style-type: none"> - Application of waste/tailings in environmental recovery in mining; - Backfill (returning the tailings to the mine). 	

Table 5: Tailings reduction and circular economy approaches.

An aerial photograph of a river delta, showing intricate patterns of water and sediment. The water is a mix of light blue, green, and brown. The sediment is a mix of light brown, tan, and white. The overall scene is a complex, organic pattern. Overlaid on the bottom left of the image are several overlapping yellow geometric shapes, including triangles and polygons, creating a modern, abstract design.

**Assessing Tailings
Reduction Range**

09



9. Assessing Tailings Reduction Range

Realistically, most current “Zero Tailings” initiatives are forms of tailings reduction. Considering that this is a relatively recent shift for the industry, definitions and conceptual approaches have been proposed, yet none has been consolidated or widely recognized as the predominant reference within the sector, and there are still no established standards or international regulatory bodies providing clear criteria for its application. Of existing initiatives, the Global Industry Standard on Tailings Management (GISTM) has emerged as the most dominant. Nevertheless, poor standardization across the industry presents several challenges. Without a common framework, it becomes difficult to objectively assess the scale, effectiveness, and impact of tailings reduction initiatives.

It is therefore necessary to develop an objective and transparent methodology to monitor progress toward tailings reduction. The same approach could allow the replacement of a binary view of “compliance” or “non-compliance” implied by “Zero Tailings,” with a graduated system capable of continuously measuring the results achieved.

9.1 Assessing Tailings Reduction Range

The theme of the MIT Global Summit on Mine Tailings Innovation (MIT Environmental Solutions Initiative, 2024), sponsored by the International Council on Mining and Metals (ICMM), classified tailings innovation into three main approaches from the Tailings Reduction Roadmap (ICMM, 2022):

- **Reduce:** Minimize the generation of new tailings through improvements in process and technical efficiency.
- **Re-use:** Repurpose existing tailings to generate value, reduce storage needs, and enhance safety.
- **Re-imagine:** Restructure processes across the value chain, with the potential to eliminate the generation of new tailings.

ICMM (2022) further classifies tailings reduction technologies by their quantitative impact potential, providing useful anchors for graduated performance measurement. Incremental projects – such as sensor-based and bulk ore sorting, coarse flotation, tailings data platforms, and waste valorization – are projected to achieve up to a 30% reduction in tailings volumes and are characterized by relatively short timeframes to first commercial use. Transformative projects – such as non-chemical extraction, no-waste mine architecture, and mechanical cutting – are projected to achieve 30-60% reduction, but require deeper redesign of mine

planning and processing routes. Disruptive projects – such as smart comminution and in-situ leaching – could theoretically approach 90-100% reduction, but remain at low Technology Readiness Levels (TRL <6) and are projected to require 10-15 years to first commercial deployment. This tiered classification provides anchors for innovation in measurable progress thresholds. Building on this, metrics introduced below add more detail by further subdividing and specifying the categories, which are ultimately applied to case studies presented in the Appendix.

Based on the ICMM framework, several technical indicators can be defined to support a tailings reduction assessment methodology, such as:

- Percentage decreased in the generation of new tailings because of improved extraction and processing efficiency.
- Percentage of residual metal recovery achieved through tailings reprocessing.
- Volume of tailings converted into co-products or byproducts.
- Volume of tailings commercialized for use in other production chains.
- Volume of tailings reused in environmental rehabilitation initiatives.
- Water efficiency (recovery and recirculation), energy efficiency, and carbon emissions associated with the applied technologies.

In addition to technical indicators, other factors can be considered to complement the evaluation of solutions adopted in pursuit of tailings reduction or elimination, such as:

- Total volume of tailings generated by the operation, which provides context for the scale of the challenge.
- Concentration of economically valuable elements remaining in the tailings, which influences the feasibility of reprocessing.
- Level of investment in applied technologies, reflecting the financial commitment required for implementation.
- Market demand for tailings-driven byproducts, which affects the potential for external industrial use and commercialization.

Incorporating these factors into the assessment framework allows for a more comprehensive understanding of the operational, economic, and strategic dimensions of the tailings reduction initiative. It is also essential to consider the existence of specific standards or guidelines that define how companies in the sector should report data related to tailings management. One example is the Global Reporting Initiative (GRI) framework, which includes specific indicators for the mining and metals sector. These guidelines, for instance, require the disclosure of the

total number and volume of tailings generated, as well as the disposal methods used, promoting greater transparency and comparability among organizations that adopt them. Following guidelines such as the one proposed by GRI enable continuous and comparative evaluation based on indicators with clear metrics, allowing for the monitoring of progress and providing greater transparency in comparing the technologies employed for tailings reduction.

9.2 Performance Scale and Classification by Tailings Reduction Bands

Many operations that self-declare as “Zero Tailings” continue to generate waste, often with undefined or uncertain reuse plans, or without technically or economically validated destinations. In such cases, the use of the term “Zero Tailings” is technically inappropriate. The solution lies in adopting more realistic and descriptive terminology that aligns with legal and environmental criteria.

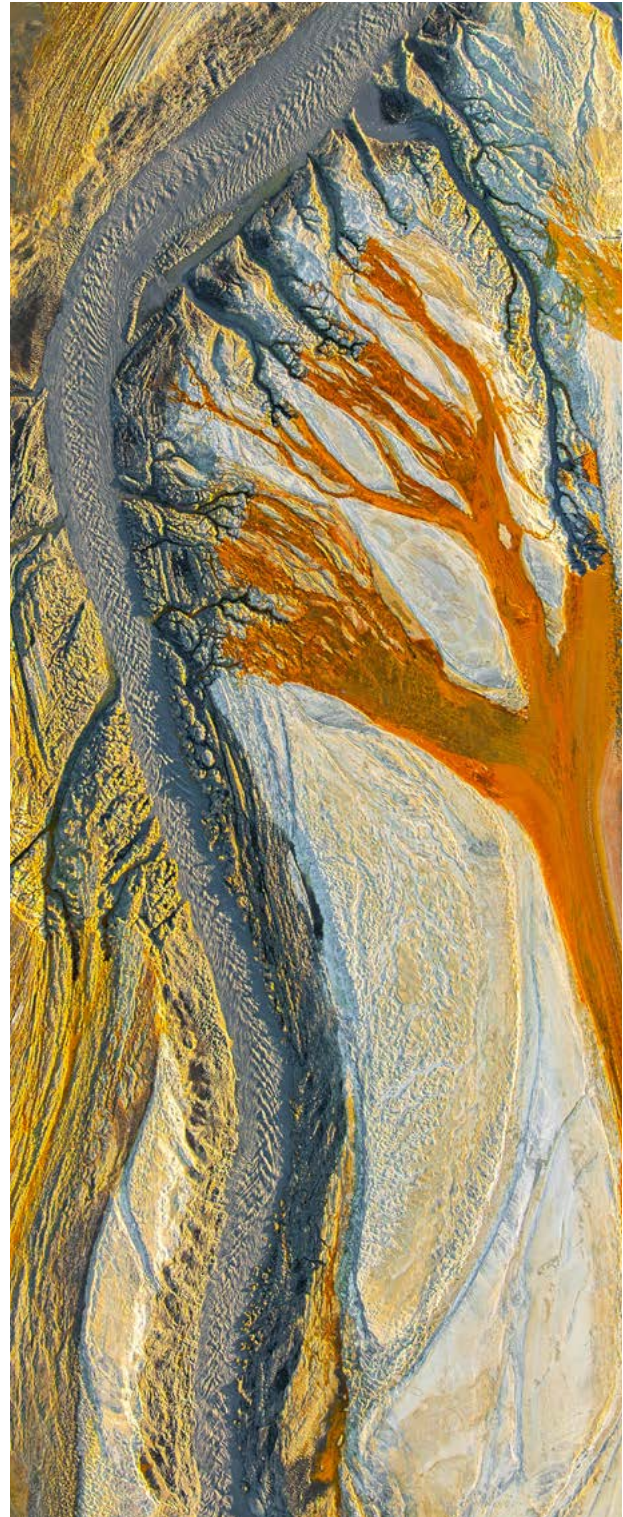
Achieving complete elimination of tailings requires exceptional geological conditions, advanced processing technologies, and integrated reuse strategies supported by strong market demand for by-products. These scenarios are highly restrictive and not representative of the broader mining industry, where mineralogical complexity, economic constraints, and logistical challenges prevail. For most operations, “Zero Tailings” remains a theoretical horizon rather than an attainable short-term objective.

Notwithstanding, modern mining operations have already incorporated cost optimization measures that inherently reduce waste generation, driven by the economic imperative to maximize resource recovery and minimize disposal costs. Even without explicit sustainability commitments, companies have adopted practices such as improved ore sorting, water recycling, and partial tailings reuse to enhance operational efficiency. This underscores the need for realistic performance benchmarks that acknowledge incremental progress while avoiding misleading claims of absolute elimination.

While eliminating tailings or operating without generating them is not yet feasible with current technologies, it is possible to determine reference bands that help assess and communicate progress more transparently and comparably. This approach enables companies to position themselves within a spectrum of technological maturity, capable of describing different levels of performance in tailings management, while acknowledging the specificities of each operational context.

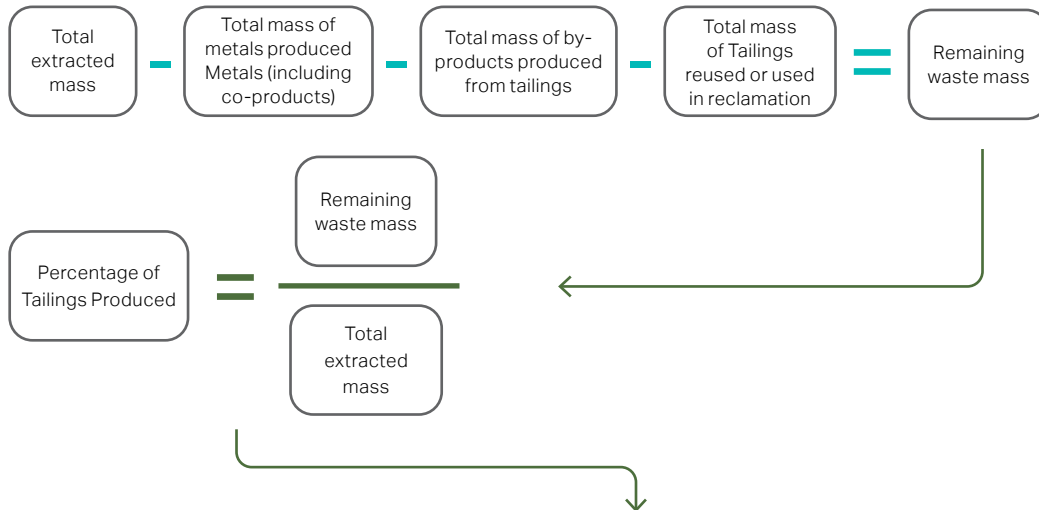
Reference bands structured around quantitative indicators, as illustrated in the following framework

(Figure 9) can be adopted by the industry to help in these assessment and disclosure processes. The “Percentage of Tailings Produced” refers to the remaining waste mass calculated by subtracting all produced metals (including co-products), the masses of any by-products obtained from tailings, as well as tailings and overburden material that are re-used in reclamation process from the material extracted. This result is then divided by the mass of material extracted to determine the tailings production rate.





Percentage of Waste and Tailings Produced



Proposed Scale for Classifying Mining Waste



Figure 9: Proposed Reference Bands.



The adoption of the proposed terminologies represents a strategic advance in how companies can plan, communicate, and validate initiatives aimed at tailings reduction. By establishing clear and graduated reference bands, it becomes possible to define more realistic goals that are compatible with the technological stage and operational context of each site, while avoiding generic or unattainable commitments. The structuring of specific criteria and measurable indicators enables transparent communication of progress, facilitates independent technical audits, and strengthens institutional credibility with stakeholders.

The proposal employs precise technical language in place of ambiguous terms that lack methodological

support, thereby significantly reducing institutional credibility risks and preventing misleading interpretations by investors, regulators, and the broader community.

The term "Zero Tailings" should not be used by companies whose operations still generate any volume of tailings, even if minor or temporary, as this compromises transparency and may lead to future mistrust or accountability issues. The adoption of more adequate terms, aligned with a performance scale, allows operations to be classified based on their actual merits.





**Toward Tailings Reduction: a Strategic
Pathway for Sustainable Mining**

10



10. Toward Tailings Reduction: a Strategic Pathway for Sustainable Mining

If tailings reduction were solely a matter of economic feasibility, the mining sector, naturally driven by cost optimization, would have already adopted these practices on a large scale. The reality is that achieving tailings elimination requires a broader commitment that transcends industrial interests. It must be embraced as a collective industrial and societal goal, supported by policy frameworks, cross-sector collaboration, and long-term investment in innovation. At its core, an operation guided by a tailings reduction proposal must seek to replace the traditional linear model of “extraction–processing–disposal” with a more efficient approach in which both products and by-products are fully utilized. This transition involves adopting clean technologies, optimizing processing routes, and integrating mining operations with other industrial value chains, such as cement, ceramics, fertilizers, and pigments.

The feasibility of higher rates of tailings reduction is inherently site-specific, shaped by mineralogical characteristics, deposit type, and the nature of gangue

minerals and contaminants. While universal solutions are impractical, certain enabling technologies and strategic approaches offer broad applicability and serve as foundational pillars for advancing this agenda, particularly through integration with adjacent industrial value chains such as cement, ceramics, fertilizers, acids and pigments.

Certain minerals exhibit high potential for “Near-Zero-Tailings” operations. These deposits benefit from simpler mineralogy, compatibility with dry processing, and viable markets for by-products. In contrast, sulfide ores and low-grade deposits require hybrid strategies focused on minimization, safe containment, and partial reuse.

Despite promising advances, several challenges hinder the widespread implementation of tailings reduction strategies. Sulfidic tailings, for instance, pose significant environmental risks due to acid mine drainage and metal leaching, requiring costly containment and long-term monitoring. Deposits with grades below 2%, such as those containing copper or nickel, generate large volumes of tailings, making full reuse or elimination economically impractical (Adrianto et al., 2023). Emerging technologies, such as bioleaching, selective hydrometallurgy, and dewatered tailings piles, offer potential solutions; however, they are not yet scalable or universally applicable.

The production of tailings is an intrinsic part of mineral processing, especially when dealing with low-grade



ores and deposits with complex mineral compositions. Therefore, tailings reduction initiatives should be understood not as a fixed technical goal, but as a horizon of innovation and responsibility, a strategic pathway that guides continuous improvement. Rather than treating tailings as a passive liability, a strategic tailings reduction framework invites the industry to reframe them as potential secondary resources. This shift in perspective aligns with broader trends in resource efficiency and the principles of a circular economy. The future of mining will be determined not by how much more we extract, but by how much less we waste.

Achieving higher rates of tailings reduction requires more than technological innovation. It demands a cultural transformation that prioritizes integrated resource management, efficient use of natural input, and the valorization of waste. Progress depends on coordinated efforts among mining companies, research institutions, regulatory bodies, and civil society.

Moreover, the reuse of tailings is constrained by market limitations, including regional variations in demand for co-products and by-products, which are often insufficient to absorb the total volume of waste. This creates a critical economic gap, as tailings-derived materials must compete with established products from other industries, which often benefit from lower production costs and mature supply chains.

Tailings reduction or elimination initiatives must be assessed not only from a technical standpoint but also through economic and ESG lenses. While initial costs may be high, long-term benefits include reduced environmental liabilities and disaster risks, improved ESG ratings and access to green financing, new revenue streams from tailings-derived products, and enhanced community relations and regulatory compliance. Strategic planning should integrate these dimensions to ensure the sustainable implementation of these initiatives.

In a world where demand for minerals continues to rise, tailings reduction should become a standard objective for new mining projects, not as a promotional statement, but a strategic commitment to reducing liabilities and minimizing long-term environmental legacies. Ultimately, tailings reduction must not be seen as fixed endpoint but a strategic horizon that integrates innovation, economic planning, and ESG principles to drive substantial reductions and reshape the industry's environmental footprint.

While a fully "Zero Tailings" scenario may not yet be feasible, the adoption of practices that significantly reduce tailings volume already represents a crucial step. Every advancement in tailings reduction should be understood not merely as an operational efficiency measure, but as a collective safety strategy essential to making mining less vulnerable and more aligned with long-term sustainability goals.

Disclaimer

11



11. Disclaimer

a. Purpose and Scope of the Report

This report is intended as a high-level technical assessment of the concept of “Zero Tailings” in mining operations. It is based exclusively on publicly available information (mostly provided by the mining companies themselves), including case studies, industry reports, academic publications, and corporate communications. The objective of this document is to stimulate constructive technical discussions regarding the feasibility, classification, and evaluation of tailings storage facilities (TSFs) and tailings management practices globally.

b. Limitations and Interpretative Nature

The findings, analyses, and conclusions presented herein are not definitive and should not be interpreted as an exhaustive or authoritative evaluation of any specific mining operation, company, or technology. The concept of “Zero Tailings” is inherently aspirational and subject to interpretation, as it lacks universally accepted definitions or standards. This report acknowledges the complexity and variability of mining practices, geological conditions, and technological advancements, which may lead to differing opinions or interpretations.

c. Reliance on Publicly Available Information

The report relies solely on publicly disclosed data and does not include proprietary, confidential, or unpublished information from any mining company or entity. As such, the accuracy, completeness, and reliability of the data used are contingent upon the original sources. Any discrepancies, omissions, or inaccuracies in the underlying data are beyond AECOM’s control.

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This report does not seek to endorse or criticize any specific company, technology, or initiative. References to corporate claims, case studies, or industry practices are included solely for illustrative purposes and should not be construed as an evaluation of their validity or effectiveness. The use of terminology such as “Zero Tailings” or similar expressions is analyzed within the context of corporate communications and sustainability narratives, rather than as a technical certification.

e. No Legal or Financial Advice

The report is not intended to provide legal, financial, or regulatory advice. Readers are encouraged to consult qualified professionals and relevant authorities for guidance on compliance, risk management, and operational decisions related to tailings management.

f. Exclusion of Liability

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i. Encouragement of Dialogue

AECOM emphasizes that the report is designed to ignite technical discussions and foster collaboration among industry stakeholders, policymakers, and researchers. It is not a prescriptive document but rather a starting point for exploring innovative approaches to tailings management and sustainability in mining.

An aerial photograph of a river delta, showing intricate patterns of water channels and land. The colors range from light tan and grey to deep orange and red. A large, semi-transparent yellow geometric shape, resembling a stylized star or a cluster of overlapping triangles, is overlaid on the left side of the image. The text 'References' and the number '12' are centered in the upper-middle part of the image.

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12



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An aerial photograph of a river delta, showing a complex network of channels and floodplains. The water is a light, milky color, contrasting with the green and brownish vegetation of the land. A large, semi-transparent teal geometric shape, composed of several overlapping triangles, is positioned on the left side of the image. The word "Credits" is centered horizontally across the middle of the image, with a thin black horizontal line underneath it.

Credits

Credits

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