

Green Engineering Approaches to Tailings Management in the Mining Industry: Chemical Process Design, Water Recycling, and Zero-Waste Goals (A Review)

AKINTUNDE S. SAMAKINDE¹, VINCENT B. AROHUNMOLASE², DAWUDA L. MASSAQUOI³,
CHIDUBEM B. ONWUGHARA⁴

^{1,4}Department of Geology and Physical Science, University of Ilorin, Kwara State, Nigeria

²Department of Chemical Engineering, Pamukkale University, Denizli, Turkey

³Department of Civil Engineering, Pamukkale University, Denizli, Turkey

¹<https://orcid.org/0009-0009-8144-997X>

²<https://orcid.org/0009-0001-6210-1523>

Abstract- Modern society could not do without mining as the raw materials it provides support not only the industries making up everyday life such as construction, energy, electronics, renewable technologies, among others. However, this improvement is at a price: every year, billions of tonnes of thinly-ground mineral tailings are produced, which is an environmental, social, and technical burden. Traditional techniques of tailings disposal most remarkably slurry storage behind huge earthen dams are being acknowledged as being unsustainable. Not only do these facilities use colossal amounts of water but are also always under the looming threat of disastrous collapse, as was witnessed with Brumadinho in Brazil. The concepts of green engineering can provide a radical way to rethink the management of tailings. These principles instead of viewing tailings as a type of water inevitability resulting from the mining process, emphasize process redesign, water conservation, and resource recovery to synchronize the mining process with the goals of a circular economy and sustainability. This literature review paper discusses three pillars of green engineering in managing tailings: (1) making chemical process design innovations to minimize tailings volume and increase dewatering efficiency; (2) developing improved water recycling systems to establish near-closed-loop cycles; and (3) developing zero-waste approaches that use tailings as an asset instead of a liability. This paper identifies the gains, constraints, and prospects of these strategies by developing evidence based both on the industry case studies and the scholarly literature in Europe, the Americas, Asia and Africa. Finally, green engineering is not only a requirement

in terms of environment but also a social and economic requirement of the future of mining.

Keywords: Tailings Management, Green Engineering, Chemical Process Design, Water Recycling, Zero-Waste Mining, And Circular Economy.

I. INTRODUCTION

Mining has never had any other name but dual. On the one hand, it is the foundation of almost all new things in the contemporary world: copper wiring in houses, steel in bridges, lithium in electric cars, and rare earth materials in mobile phones and wind turbines. Conversely, it produces huge environmental footprints. The most obvious and largest are tailings, which is a slurry of ground rock, water and remaining processing chemicals when valuable minerals are removed. Miners can generate tens to hundreds of tonnes of tailings per tonne of finished metal (Martinez, 2019). These are normally dumped in designed impoundments referred to as tailings storage facilities (TSFs). Over many decades, it has been assumed that the waste can be confined indefinitely and the industry can produce more without radically changing the approach to waste. However, this model is becoming less and less tenable. The problems are threefold:

- i. Water demand and scarcity. In traditional slurry tailings, the slurry tailings are less than 30-50% solids. It implies that the mining activities have to maintain the huge amounts of water flowing through their systems, which need to be

replenished on a regular basis with freshwater supplies (rivers, aquifers, or desalination facilities etc.) (Theodore & Dupont, 2019). In arid areas like in the Atacama Desert of Chile or in southern Spain, where water shortage is already severe, this demand poses intense competition with agriculture and populations.

- ii. Environmental contamination. A lot of the tailings have sulfide minerals and thus when they are exposed to air and water, they oxidize to produce sulfuric acid. This causes a chain reaction which causes toxic metals to leech into the immediate soils and waterways, a process referred to as acid mine drainage (AMD). The history of the old mines throughout Europe and North America serves as an eye-opener to the process of how long and expensive such contamination can be (Liang & Thomson, 2009).
- iii. Structural risk. Probably the most apparent threat is caused by dam disasters. In 2019, the 12 million cubic meters of sludge that escaped the Brumadinho dam caused 270 fatalities and contaminated 120 kilometers of river. These catastrophes are not occasional accidents but renal occurrences, which underscores the vulnerability of using large surface impoundments as the conventional disposal program (Bowell, et al., 2023).

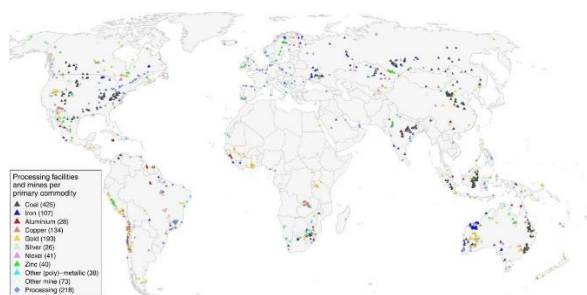


Figure 1: Global map of facilities covered in the open database on global coal and metal mine production.

Source: Jasansky et al., 2023

The three pressures, water stress, environmental liability and social accountability have provided a turning point to the mining industry. Beyond containment, regulators and investors as well as Indigenous communities and NGOs are seeking solutions that are more focused on prevention and transformation. In this case, green engineering comes out as a philosophy. Fundamentally, green engineering

is using systems thinking and concepts of sustainability into chemical processes, materials management, and resource efficiency (Mulvihill, et. al., 2011)

Instead of posing the question how do we contain tailings more safely, green engineering asks how can we produce less tailings, recycle more water at least, and transform the rest into useful products?

Considering the tailings, this approach is characterized by three independent strategies:

- i. Designing chemical processes in a way that minimizes the amount of waste generated and increases the amount of water that could be collected at the point of generation.
- ii. Water recycling and reusing the water to decrease the reliance on freshwater sources and ensuring the closed-loop circulation.
- iii. To follow the zero-waste principles by using tailings as a second resource which can be reprocessed or reused in other industries.

Each of the strategies is discussed below starting with chemical process design innovations.

II. GREEN CHEMICAL PROCESS DESIGN.

2.1 High-Density Thickening

The development of high-density thickening technologies has been one of the initial changes in the direction of greener tailings management, (Cacciuttolo Vargas, & Marinovic Pulido, 2022). Traditional thickeners tended to produce tailings that had relatively low solids content and as such, large ponds were necessary to decant the water. On the contrary, modern deep-cone thickeners generate a deeper underflow, which is normally 65-75% solids. There are two significant advantages to it: first, there is a reduced amount of water retained in the tailings to be recycled; second, the tailings sent to impoundments has a steeper slope and takes less space (Barrera et al., 2015). Water recoveries up to 70 percent by high-density thickening have been reported in operations in the copper industry and Scandinavian polymetallic mines. In addition to the water savings, such facilities decrease the area of TSFs, which is always important in mountainous or land-limited areas. The increase in

the scale of these thickeners however, is a capital consuming project, and in variable ore conditions, reliability in operations is a challenge, (Barrera et. al., 2018).

2.2 Paste Tailings and Underground Backfill.

Paste technology is another advancing technology that gives an opportunity to obtain a thickened stream of tailings consisting of 75-85 percent solids, (Wu et. al., 2011). In contrast to the traditional slurries, paste tailings are not separated into sand and fines but take the form of a homogenous mass of high yield stress. The paste can be pumped directly into underground voids using this property and can then harden and offer structural support (Yilmaz, & Guresci, 2017).

The advantages are twofold: It reduces the need for surface storage and contributes to the structural stability of underground stopes, lowering the risk of roof collapse and improving ground support in deep mining (Cacciuttolo et al., 2023). However, paste systems are power intensive and energy consuming and binders such as cement are added to increase the cost and the carbon footprint, (Naqi & Jang, 2019). These trade-offs need to be thought over yet in an environment where surface disposal is very limited, the green-engineering solution of paste backfill is very elegant.

2.3 Filtered and Dry-Stack Tailings.

The greatest innovation of recent decades was perhaps the adoption of filtered tailings, commonly referred to as dry stacking. Tailings may also be dewatered down to less than 20 percent moisture using vacuum or pressure filtration to form a damp sand-like substance, (Davies, 2011; Icold, 2023). This can then be piled up and compacted into engineered piles, without the use of large water impoundments. The benefits are very strong: more than 90 percent of process water can be reused, liabilities related to closure are minimized, and the threat of dam failures are practically removed (Schafer, Beier, & Macciotta, 2021). Gold and base metal activities in Finland and Spain in Europe have adopted dry stacking despite the cold climate that will otherwise make management of frozen tailings

difficult. The key challenges are cost and scale: filtration units are capital intensive and dewatering of fine-grained tailings in volumes of millions of tonnes per year is a technically challenging task. However, with the increasing stress on water and social pressure, dry stacking is now being considered not as an option but as a new standard of the future, (Furnell, et. al., 2022).

2.4 Upstream Chemical Optimization.

Tailings are not formed at the dam, but by the chemistry of the upstream processing. Developments in flotation reagents, pH control, and dispersants have enhanced the dewatering properties of tailings and have also facilitated greater recycling of process water (Li et al., 2019). Notably, the trend is towards biodegradable reagents that are less toxic and have little impact on metallurgical performance of recycles water. Fining reagent choice helps the operations to minimize fines entrainment, lower the development of colloids and enhance the work of thickeners and filters downstream, (Bista, 2022). These are relatively inexpensive modifications as compared to the construction of new infrastructure, which demonstrates strength of green chemistry at the process level, (Beach, Cui, & Anastas, 2009).

2.5 Secondary Metal Recovery

Finally, increasing evidence demonstrates the prospect of re-mining tailings to extract valuable and important metals, (Maest, 2023). Historical operations in most instances left behind tailings that had metal concentrations that are now economically viable. The remaining copper, gold, or even a part of the rare elements can be extracted using hydrometallurgical techniques (including bioleaching, solvent extraction, etc.) (Simate & Ndlovu, 2021). An example is the European pilot projects that are extracting cobalt and scandium out of old tailings of nickel and bauxite, which is in line with EU plans of critical raw materials security. In addition to recovering resources, reprocessing minimises the hazardous element of tailings, which minimises the environmental liability in the long term.

Table 1. Comparative Characteristics of Major Tailings Management Options

Technology	Solids Content (%) by weight)	Water Recovery (%)	Capital Cost (relative)	Key Advantages	Key Limitations	Example Region/Case
Conventional slurry dams	30–50 %	< 50 %	Low	Established, low upfront cost	High water use, dam-failure risk	Global legacy sites
High-density thickened	65–75 %	50–70 %	Moderate	Reduced water loss, steeper beach slope	Large thickeners needed, energy costs	Chile, Australia
Paste tailings/backfill	75–85 %	~70 %	High	Underground disposal, reduced surface risk	Rheology control, binder cost	South Africa, Canada
Filtered/dry stack	80–90 %	> 90 %	High	Minimal water use, safer long-term closure	High energy and O&M costs, climate-dependent	Spain, Finland
Zero-liquid-discharge (ZLD)	N/A	~100 %	Very High	No effluent, full water recovery	Energy intensive, costly	Spain (Las Cruces)

Source: Compiled from Zhang et al. (2023a)

III. WATER RECYCLING AND ZERO-LIQUID-DISCHARGE (ZLD) SYSTEMS

Mining is commonly known to be one of the most water intensive industries. Water is the invisible force behind nearly all the process stages, starting with ore grinding through to flotation, leaching, dust suppression and slurry transport. In the case of tailings management, specifically, water serves both as a carrier medium in the fine solids produced during ore processing, and as one of the most valuable as well as vulnerable resources at the mine site. Water availability not ore grade is a determinant of a project being viable in many operations, especially in the arid regions of South America, southern Europe, western Australia, and some parts of Africa (Meißner, 2021).

In the past the industry had been using water as a free utility. The tailings slurries containing 30%-50% solids were pumped to storage tanks where water slowly decanted and evaporated, (Morrison, 2022). Such a practice was wasting billions of cubic meters in a year and was causing significant losses in the form of seepage and even dam failure. Green engineering is rebranding the concept of water, however, not as a supplementary factor, but as a recyclable, limited resource today. The new paradigm is to loop it back--recovery, treatment and reuse of water until virtually no liquid passes the mine fence, (Mitchell, et. al., 2022).

3.1 Closed-Loop Water Circuits

The principle of closed-loop circuits is the basis of modern water management. Mines extract and recycle

process water in multiple locations such as thickener overflows, filtrates of vacuum filters, pressure filters, cooling water, pit dewatering, and even stormwater instead of constantly sourcing fresh water through rivers or aquifers (Joshi, 2020). This aspect has enabled numerous operations to achieve 70%-85% rate of water recycling, which saves their freshwater footprints drastically. There is greater control of these loops due to the technological advancements. The ionic composition, turbidity and dissolved oxygen in the water are currently observed in near real time using online monitoring devices to enable operators to adjust the reagent dosages to ensure flotation performance remains consistent (Chen, Ngo, & Guo, 2013; Younos & Heyer, 2015). This is important as the water that is recycled contains dissolved solids of sulfates, chlorides and other unused reagents that may disrupt the separation of minerals. As an example, magnesium that is higher in recycled water can lead to more use of lime in pH corrections, and higher chloride in recycled water can destroy the froth (Sánchez Ortega, 2019). Recycling may have a counterfeit effect of reducing the recovery without monitoring and adaptive chemistry.

The most important strength of closed-loop systems is that they often incur lower incremental capital cost compared to full-scale advanced treatments, because they reuse existing infrastructure (thickeners, tanks, pumps) with moderate modifications. Indeed, closed-loop recycling in mines has been shown to be more cost-effective and practical than some advanced treatment options under many circumstances (Kinnunen et al., 2021). The trade-off, however, is the complexity of operation: each ore mineralogy and each seasonal inflow and reagent scheme are changing the water quality all the time. Therefore, closed-loop is a fast-moving balancing process that needs talented metallurgist, reactive chemical plans and in some cases, bleeding of water partially when pollutants accumulate, (Younger, & Wolkersdorfer, 2004).

3.2 Zero-Liquid-Discharge (ZLD) Solutions.

Zero-liquid-discharge (ZLD) has become the most ambitious target to be achieved with sites with a severe water stress or tough discharge permits. The idea is straightforward: the liquid effluent is not discharged out of the site. Practically, ZLD needs to be a mixture

of membrane separation, thermal evaporation, and crystallization. A common ZLD flow chart starts with pre-treatment- lime softening or chemical precipitation to remove the hardness and suspended solids. Ultrafiltration and reverse osmosis (RO) are then used to concentrate dissolved salts. Multi-effect evaporators are then used to treat the RO reject stream that still contains a lot of water. Lastly, the strongly saline water is sent to crystallizers, where solid salts are obtained to be disposed of in landfills or in certain instances, reused industrially (Zhang et al., 2023b). The sterilized water as high as 95 percent of the original stream is pumped back into the plant.

ZLD has a number of strong points. It removes the surface water discharges and therefore, eliminates river or aquifer contamination. It also makes sure that it is able to operate with little or no freshwater input, a priceless attribute in hyper-arid locations such as the Atacama Desert or the semi-arid mining belts of Spain. In addition, the salts obtained in crystallizers can be by-products in their own right that are commercially marketable in some situations.

However, ZLD is not a panacea. It is power-consuming as it needs approximately 7-10 kWh of treated water per cubic meter (Zhang et al., 2023b). This translates to high operating costs, which is normally USD 2-2.5 per m³ much costlier than river water extraction. The equipment is also manned by the experienced operators and is expensive to capitalize. Therefore, ZLD is typically adopted in mines only when water scarcity or stringent discharge regulations make it one of the few viable options, as stricter environmental laws increasingly push industries toward full water recovery (Tong & Elimelech, 2016).

Proposals underway are to minimize these costs. A pilot test of coupling ZLD evaporators to solar-thermal energy is underway in Spain and Italy, where the high solar irradiance can be used to compensate electricity requirements. In other studies, forward osmosis (FO) and membrane distillation (MD) have been explored as potentially less energy-intensive or thermally driven alternatives (de Nicolás et al., 2023). As renewables and waste-heat sources become more available, there is growing momentum toward renewable-powered ZLD systems as a commercially viable long-term solution.

3.3 Alternative and Nontraditional Water Sources.

In addition to recycling and ZLD, a third approach is the mere fact of the diversification of water sources out of freshwater ecosystems. Mines are turning to desalinated sea water, municipal wastewater and even untreated sea water as inputs into the process. For example, in Chile the use of seawater in copper hydrometallurgy has grown significantly in recent years, currently accounting for about 25 % of the industry's water demand (Astudillo et al., 2023) Just related efforts are being seen in Europe wherein Mediterranean mines are now starting to trial seawater flotation circuits.

Substitution needs to be made using other water. The ionic strength of seawater is too high to be treated by standard flotation, and requires different reagent suites. As an illustration, xanthates and dithiophosphates perform poorly in salty systems, and special collectors and depressants have to be used in those systems. Nevertheless, appropriately chemistry, seawater flotation can be at least as efficient as freshwater recovery when using some types of ore.

Another frontier that has not been explored well is wastewater reuse. A number of mines in South Africa and India are already treating municipal sewage effluent to an industrial level to be used in dust suppression and in mineral processing. This is an option that is an attractive alternative in Europe, where harsh urban water policies and robust infrastructure of water treatment processes means turning a liability into a resource and lessening the struggle of the mining industry against the industry of agriculture and households.

IV. STRATEGIES FOR A CIRCULAR ECONOMY AND ZERO WASTE.

The concept of zero waste brings the view of the conservation of water to a wider systems approach: the concept of tailings not existing in the form of waste, but in the form of resources waiting to be utilized. This necessitates a re-thinking of tailings as not something to be covered behind dams, but as the feedstock of new industries.

4.1 Tailings as Construction and Civil-Engineering Materials.

A direct opportunity is in the construction materials. Tailings are highly fined rock material possibly abundant in silicates, oxides and minor cementitious elements. They are able to replace sand, aggregate or even cement with the right stabilization. Studies reveals that the tailings of gold-mines to fired bricks can be substituted up to 30% of natural sand without affecting its strength (Balegami, Nkuba, & Dable, 2022). Equally, it is possible to use geopolymer concrete with high compressive strength and durability using iron-ore tailings mixed with fly ash and alkaline activators.

This method directly addresses two sustainability issues: it lowers the amount of tailings storage and minimizes the amount of quarried natural aggregates which in themselves are environmentally destructive. The main obstacle is still leaching risk. Sulfide or trace metal tailings should be stabilized, i.e. by vitrification, geopolymerization, or encapsulation, and then safely reused. Laws that govern the construction of products especially the Construction Products Regulation by the EU are very important in providing an opportunity to the market with safety in the environment.

4.2 Secondary Metal and Mineral Recovery

The secondary mining of metals and minerals occurs as the second step. Most tailings streams are not barren. Reduced ore grades imply that present day concentrators discard what would have been viewed decades ago as ore. Specifically, historical tailings usually have recoverable amounts of copper, cobalt, scandium or rare earths. They are being recovered through the advancement of hydrometallurgy and bio-leaching (Mishra, et. al., 2023). Finland, an example, has demonstrated pilot projects can extract scandium in nickel tailings, to supply the increasing demand of lightweight aluminium-scandium alloys. Cobalt is extracted in Portugal, by means of low-pH sulfide oxidizing bacterial consortia, in old copper TSFs. In addition to metals, industrial minerals, such as silica or feldspar (or even pigments) can also be found in some tailings streams and be used in ceramics or glass. It is two-fold: metal recovery is generating new sources of income and decreases the dangerous part of tailings, facilitating the process of closure and rehabilitation in the long term.

4.3 Paradigms of Dry Processing and No-Tailings.

The most radical idea is the idea of removing tailings. New beneficiation methods like dry magnetic separation, high-pressure grinding rolls and sensor-based sorting of ores enable the upgrade of ores without generating fine slurries. One example is Brazilian Vale that has led in the development of natural moisture processing of iron-ore, making no use of wet grinding, but rather dry screening and magnetic separation. This yields high grade product with coarse waste rock which can be safely stored without the use of dams (Araujo, 2003). The Scandinavian operations are also testing a sorting of ores using X-ray and laser sensors to pre-concentrate ores, it will reduce the amount of material that is fed into grinding circuits and in effect, cut down on the amount of tailings generated at the source. Although these methods are not applicable everywhere, since even the complex mineralogy of sulfide ores may need to be floated, these methods suggest a future in which some commodities are produced without standard tailing plants.

4.4 Circular-Economy Integration

Zero-waste mining, in its fundamental concept, is not about technology but it is about integrating the circular economy into mineral supply chains. The question of the circular economy is: how can all the products of mining, water, tailings, heat, or waste rock, be recycled into the input of some other process? Life-cycle assessment (LCA) tools can measure trade-offs and inform the decision-making (Northey, 2018). The policy frameworks are starting to follow this vision. Resource efficiency in extractive industries such as re-use of mine waste and valorization of tailings explicitly is demanded by the European Green Deal and the Circular Economy Action Plan (Smol, et. al., 2020). Such frameworks and financial tools as extended producer responsibility can establish further motivation in businesses to invest in tailings reprocessing, construction-material markets and dry-processing innovations. Finally, circularity changes the way of viewing mining as a linear process of dig-use-dispose into a closed-loop of materials, with even tailings becoming a part of a larger industrial ecosystem.

V. INTERNATIONAL CASE STUDIES AND INTERNATIONAL PERSPECTIVES.

Regional environmental pressures, regulatory frameworks and economic contexts have been historically reflected in the management of mine tailings. Nowadays, globalization of mining finance, community activism and international standards of governance are increasing the spread of green engineering innovations. Looking at the experience of other continents, one can see both general problems and specific regional reactions that jointly explain the world trends in the management of tailings.

5.1 Europe: Regulatory-based Innovation and Resource efficiency.

Compared to other parts of the world (e.g. South America or Asia) Europe has fewer active large-scale mines, yet it has a history of mining, and a policy environment that focuses on sustainability. The Water Framework Directive and the Mining Waste Directives of the European Union (2006/21/EC) have put in place a strict guideline on water discharge and safety of a waste facility. Such legal tools have been an effective catalyst to technological advancement in tailings management.

As an example, Las Cruces copper mine in Spain is often used as a model of sustainable management of tailings and water. The mine is situated in the dry Andalusian area, and the water management system applied is a zero-liquid-discharge (ZLD) system, which combines membrane filtration, evaporation, and crystallization system. Its operations employ advanced water purification and reuse methods (membrane filtration, reverse osmosis, etc.), enabling substantial recycling of process water and reducing reliance on freshwater sources (Baquero et al., 2016). Despite its energy consuming nature, the project exhibits technical feasibility of closed-loop systems as long as the systems conform to regulatory pressure and community expectations. Another European emphasis, which is exemplified by Terrafame operations in Finland via the Talvivaara nickel mine, is to minimize the environmental hazards posed by massive impoundments of water in vulnerable lake regions. The mine shifted to high-rate thickening and more water recycling following the acid drainage and leakage in the early 2010s (Kauppila et al., 2013)

These modifications minimized the loadings of the pollutants to the local rivers and demonstrated the

worth of adaptive engineering as a subject of social criticism. European case studies highlight that good governance and enforcement of regulations can speed up the use of improved technologies. The European Union's Circular Economy Action Plan also promotes tailings valorization. For instance, pilot projects in Portugal and Sweden are re-mining old deposits to extract cobalt and rare earth elements, linking resource recovery with the EU's strategic agenda on critical raw materials.

5.2 North America: Water, Safety and Stakeholder Pressure.

There is a twofold focus on safety and conservation of water in North America. The dam failures at Mount Polley in 2014 in Canada, the most high-profile, spurred regulatory changes and demands by communities to find alternatives to traditional slurry dams that would be safer. Since that time, Canadian mines have made large investments in paste backfill and thickened tailings which minimise water consumption and geotechnical hazards. One such mine is the New Afton copper-gold mine in British Columbia where thickened tailings are used with underground paste backfilling. The method enables the mine to manage a high percentage of its tailings underground and eliminate the need to use surface facilities as well as minimize its risk to its neighbors. In British Columbia, the Red Chris mine has been the first to use filtered tailings as a component of a hybrid system, which is an indication that large-scale filtration is being taken seriously in North American circles.

Water shortage in the arid West of the United States has motivated copper producers to experiment with dry stacking and incorporation of solar-powered units of ZLD. Water allocations are tightly controlled in Nevada, Arizona and New Mexico which have become testing grounds to new forms of managing water. Meanwhile, Indigenous communities and local stakeholders have exercised an increasing influence demanding companies to consult them clearly and provide long-term assurances of the environmental performance. North American examples emphasize the importance of community and investor activism as two of the primary change enablers. Following Brumadinho, a number of Canadian pension funds

started insisting on companies in their portfolio to comply with the Global Industry Standard on Tailings Management (GISTM), which places financial pressure in addition to regulatory compliance.

5.3 Latin America: The response to the transition to water stress and dam safety.

One of the most significant contributors to water substitution and dry processing in the world is Latin America whose copper and iron-ore mines rank among the largest in the world. In Chile, the largest copper producer in the world, shortage of freshwater in the Atacama desert has necessitated corporations to adopt seawater and desalinated water. The Escondida mine which is the largest copper mine in the world has one of the biggest desalination plants in the mining industry. Recycled process water is then mixed with the seawater, which allows the processes to be operated without considerable freshwater extraction. This system involves tailings thickening and reusing process water, which demonstrates how a site-specific scarcity of water may inspire creativity.

Another dramatic trend is Brazil. After the disastrous Fundao (2015), and Brumadinho (2019) dam failures, everyone lost faith in slurry impoundment, (Oboni & Oboni, 2020). In response, the Brazilian government and companies like Vale have pledged to phase out upstream tailings dams and strengthen safe dam management practices (Oboni & Oboni, 2020). Dry crushing, screening and magnetic separation causes the ores to be upgraded, as wet tailings are not produced. Although it cannot be generalized across the types of ores, the experience of Brazil shows how crisis-based reforms can shift a whole industry toward more sustainable and safer practices. Latin America, therefore, shows an example of how scarcity (water) and crisis (dam collapses) are transforming rapidly.

5.4 Africa: Tailings as Development Resources.

With infrastructure and finance limited, the mining industry in Africa is beginning to experiment with tailings reprocessing in order to produce economic and social output, (Boocock, 2002). The mines in South Africa, both gold and platinum, have led the way in using tailings as backfill and recycling of the other metals that were deposited in antique dumps. Pilot projects in Zambia and the Democratic Republic of

Congo use bio-leaching on copper-cobalt tailings to get more value out of the tailings, and minimise environmental risks. This is in line with the African Union Agenda 2063 which recommends harnessing the natural resources towards sustainable development, (Ufomba, 2020). One of the critical ones is community impact in Africa. Several of these mining impacted societies are dependent on agricultural or fishing activities down the river of tailings plants. Programs that lessen the pollution of water by recycling and reprocessing hence provide social and environmental benefits. Nonetheless, absence of investments and irregular enforcement of regulations are still substantial obstacles, (Mensah, et. al., 2015, Kumar, et. al., 2021).

5.5 Asia-Pacific: High-Scale Innovation and Change that is Policy-Based

An amalgamation of several of the largest mining projects, and quickly shifting levels of policymaking, make up the Asia-Pacific region. The arid climate and high expectations of the people have seen Australia become a world leader in paste and thickened tailings technologies. Western Australia major operations work with thickened tailings, high water recycling, and progressive rehabilitation, and combine environmental performance and corporate reputation management. Tailings is a national issue in China, which happens to be the largest producer of rare earth elements in the world. There are also policies by the government to subsidize dry stacking and re-mining of the old tailings to extract the important metals in addition to minimizing pollution (Liu et al., 2023). This is an implication of a state-led drive to efficiency of resources and it is consistent with the wider agenda of ecological civilization in China. Collectively, Asia-Pacific case studies emphasize the role of scale and state policy. In the case where governments set specific sustainability objectives, the industries are usually forced, and encouraged, to invest in more environmentally friendly technologies.

VI. BARRIERS AND ENABLERS

Even though it is clearly shown that the technical potential of green engineering solutions to tailings management is discovered, it is not evenly implemented. A subtle comparison of the barriers and enablers will be critical in explaining why certain

technologies are at the niche and others at the mainstream.

6.1 Barriers

- i. Capital Costs and Economics: High technology filtration, ZLD and dry processing is costly in terms of capital investment. These costs are prohibitive when it comes to smaller or financially constrained operations. The cost of running it is also a limiting factor because of the energy needs to run filtration or evaporation.
- ii. Ore and Site Characteristics: Not all the tailing technologies can be transferred. As an example, fine grained or clay-based ores can clog filters, whereas in high rainfall climates dry stacking can be unreliable. Feasibility is determined by local hydrology, topography and ore mineralogy.
- iii. Regulatory Misalignment: In other areas, the non-existence of new regulatory frameworks unintentionally stimulates the use of the old slurry dams by failing to cover the closure liabilities in the long run. Processes of permission can also prevent the use of innovative solutions.
- iv. Institutional and Knowledge Gaps: Most mining companies especially those operating in the developing economies do not have the in-house expertise to design, operate and monitor sophisticated systems. Knowledge transfer and capacity-building are burning issues.

6.2 Enablers

- i. Technological Innovation. The costs of green technologies are being brought down and the reliability is also being enhanced by enhancing the design, materials science and process control of the filters. Modular filtration units such as these, enable a gradual adoption as opposed to an all-or-nothing investment.
- ii. Policy and Regulation. Good regulatory conditions, such as in the EU, provide a predictable motivating factor to businesses to invest in less damaging and more environmentally friendly technologies. Global standards such as the Global Industry Standard on Tailings Management (GISTM) are also driving towards convergence to the best practices.
- iii. Economic Drivers. Increasing demand on such crucial minerals like cobalt, nickel and rare earths

is transforming tailings into prospective resource deposits. Tailings reprocessing would enhance the business case of sustainable management when they generate revenue.

- iv. Social and Shareholder Pressure. Social license to operate and ESG (environmental/social/governance) metrics are becoming more and more crucial. The transparency of tailings safety and sustainability reporting has become a major institutional investors requirement. Corporate change has been a great incentive through this outside pressure.

VII. FUTURE DIRECTIONS

- i. The future of tailings management is one that indicates integration of green engineering, digital innovation and circular economy concepts.
- ii. Making Digital Twins and Predictive Monitoring. Combining real-time sensors, drones, and AI predictive models will allow monitoring tailings facilities, balancing water and materials in the most efficient way possible. This is able to save on the cost of operation and catastrophic risks.
- iii. Hybrid Systems. New mines could combine several techniques--filtered tailings on the surface, paste backfill in the underground mine, and reprocessing old deposits selectively. These hybrid solutions permit site-specific optimization to take place.
- iv. Combination with Renewable Energy. The energy intensity of ZLD and filtration systems will be subsidized with the help of renewable energy. Carbon intensity can be reduced through solar-thermal evaporation, wind-powered pumping, or geothermal heating, to assist in recovering water.
- v. Policy convergence on a global level. The GISTM and the EU regulations are establishing standards that can be followed by more global harmonization. The green engineering in tailings can eventually change into the optional or the expected one.
- vi. Socioeconomic Integration. The opportunities that tailings reprocessing and reuse present are the local development in the form of new industries (e.g., construction materials) and employment. Community benefits should be incorporated in the

tailings projects this way creating enduring social license.

CONCLUSION

Tailings management is the centre of environmental and social issues in the mining business. It is also however a golden chance to envision mining in the perspective of green engineering. Europe, North America, Latin America, Africa, and Asia-Pacific case studies show that development is not only possible but it is also being implemented. In places where it is highly regulated, where water scarcity is acute or disasters have imposed change, new practices including filtered tailings, zero-liquid-discharge system, substitution of seawater and dry processing are shifting out of pilot to mainstream.

Barriers still persist such as high costs, technical site limitations and inconsistent enforcement of regulations. Nevertheless, facilitating forces, such as technological innovations, investor demands, policy changes and increasing awareness of tailings as a by-product are gradually shifting the power. Tailings management is likely to become multifaceted, digitalised, and circular, where safety, water stewardship, and resource recovery will become an essential element of the mining process. Tailings become an active part of a regenerative mining economy in this vision and cease to be a passive liability.

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