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A Review on Rare Earth Elements (REEs) in Mine Tailings: Mineral Hosts, Extraction Chemistry, and Recovery Potential

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Abstract: *The rare earth elements (REEs) are the essential elements of modern technologies such as renewable energy systems, electric vehicles, and sophisticated electronics. In spite of the name, REEs are quite common in the crust of the Earth, but they are seldom found in economically viable concentrations. Mine tailings (remains of mining phosphate, iron, carbonatite and rare metals) in Africa, include huge amounts of REE-bearing minerals, monazite, bastnasite, xenotime and allanite. These materials constitute a relatively unexploited secondary resource that would fit the goal of sustainable mining and the circular economy. This review paper discusses the phenomenon, mineral associations, and the mining chemistry of REEs in African mine tailings, with particular focus given to selective methods of leaching appropriate to local conditions. The paper identifies the geological provinces with the greatest amount of REE-enriched residues, an analysis of the effectiveness of different leaching reagents, and environmental and economic considerations. Results suggest that African tailings may be a valuable alternate REE source with enhanced hydrometallurgical facilities, thorium handling techniques, and interregional collaboration. Through valorization of current mine wastes, Africa will gain by cutting environmental liabilities and also bolster its place in the global supply chain of REE.*

Keywords: *Rare earth elements, Mine tailings in Africa, Selective leaching, Hydrometallurgy, Sustainability, The circular economy.*

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1.0 Introduction

Rare earth elements (REEs) represent a category of 17 chemically related metals representing the 15 lanthanides, scandium and yttrium, (Unsworth, *et al*., 2020). Although REEs are relatively abundant in the Earth's crust, their dispersed occurrence and complex mineralogical associations mean that economically extractable concentrations are uncommon, thereby constraining primary production. They are essential to many clean-energy technologies with their unique magnetic, luminescent and catalytic properties including wind turbines, electric cars, and energy efficient lighting (Arshi *et al*., 2018). With the world becoming increasingly energy conscious, there has been a spike in the demand of REEs, specifically neodymium (Nd), dysprosium (Dy), and terbium (Tb). This growing demand has intensified global efforts to diversify REE supply chains away from their current concentration in China, which dominates primary REE production and processing. This has led to a rush to diversify the supply sources other than China that now dominates global production of REE, (Goodenough, Wall & Merriman, 2018).

Africa possesses vast and geologically diverse mineral resources; however, despite extensive mining activities, the continent remains marginal in the global rare earth elements (REEs) market. Its numerous mining activities and particularly the mining of phosphate, iron and the rare metals have produced massive mine tailings which continue to host significant concentrations of REE. These tailings commonly contain REE-bearing minerals such as monazite, bastnäsite, xenotime, and allanite, preserved in fine-grained or chemically altered forms that are often overlooked in conventional mining operations. In the past, these tailings were wastage because of the lack of processing technology or poor economic interest. Nevertheless, the development of selective leaching, solvent extraction, and biohydrometallurgy currently allows the recovery of those residues (Yao *et al*., 2018). The reprocessing of REE-bearing tailings is associated with a set of advantages: decreasing the negative effects of discarded sites on the environment, creating additional sources of revenue, and promoting the development of sustainable industrialization in the context of the African Mining Vision (AMV). Moreover, the recovery via tailings complies with the Sustainable Development Goal (SDG) 12 that ensures the use of resources responsibly and the reduction of waste, (Ferronato, & Torretta, 2019). From a circular economy perspective, tailings reprocessing represents a strategic pathway for transforming legacy mine wastes into secondary critical-material resources while simultaneously mitigating long-term environmental liabilities.

Despite these opportunities, systematic research on the recovery of REEs from African mine tailings remains limited. Existing studies are largely site-specific, focus on isolated mineral systems, and rarely integrate mineralogical characteristics with extraction chemistry and regional economic considerations at a continental scale. The existing literature is fragmented, localized, and seldom written into a continent. Furthermore, other problems including thorium co-occurrence, reagent availability, and economic feasibility, are also issues that demand concerted efforts. In particular, the co-occurrence of radioactive elements such as thorium, variability in tailings composition, and limited access to specialized reagents pose significant technical and regulatory challenges for sustainable REE recovery in African contexts.

This review therefore provides a comprehensive synthesis of REEs in African mine tailings, examining their mineral hosts, extraction and separation chemistry, and recovery potential, while highlighting technological gaps, environmental constraints, and opportunities for sustainable integration into global REE supply chains.

2.0 Distribution of REEs in Africa: Geological

Africa has one of the most geologically diverse terrains in the world, most of which are also endowed with rare earth elements (REEs) as shown in Fig. 1, (Abubakar, 2018). These resources are linked primarily to carbonatite complexes, alkaline igneous intrusion, and phosphate bearing sedimentary basins. Whereas in recent decades the major REE deposits have attracted interest, a secondary resource that has not been fully explored is mine tailings produced by these systems, (Goodenough, Wall & Merriman, 2018). The geological distribution of the REEs in Africa is due to the diverse tectonic and magmatic history of the continent including cratonic, rift and Proterozoic alkaline provinces.

2.1. Southern Africa

Some of the most examined REE-provinces in the continent are found in Southern Africa. One of the most famous ones is the Palabora Complex in South Africa. It is a carbonatite-phoscorite compound that yields copper, apatite and vermiculite, bastnasite and monazite are significant REE mineral in the ore and tailings (Giebel, 2019). Past mining at Palabora has produced extensive amounts of fine-grained tailings with up to 0.8 wt%

total rare earth oxides (TREO), which is a potentially attractive recovery target when recovered via selective leaching.

To the north again, the Steenkampskraal, in South Africa, is an ancient thorium mine that is now known to be one of the richest deposits of monazite in the world, (Heikal, 2020). Historical operations contain light and heavy REEs in their tailings as well as a large amount of thorium (ThO_2 up to 0.3 wt). Studies at the University of the Western Cape have shown that with a controlled sulfuric acid leached, over 90% REE can be recovered and thorium remains immobilized safely (Venter, 2018).

The Lofdal Rare Earth Project in Namibia is a unique geology consisting of xenotime and eudialyte minerals that have rich heavy REEs including dysprosium and yttrium. The tailings and the low-grade areas around it have high ratios of HREE to LREE, making them strategically important in balanced REE supply chains (Pell, 2019).

2.2. East Africa

There are many East African Rift System alkaline complexes containing REE potential. One of the most studied ones is the Kangankunde Carbonatite Complex in Malawi. It is composed of bastnasite and monazite bearing carbonatites mined periodically as a source of niobium and REE. It is estimated that tailings of these operations contain 1.0-2.0 wt % TREO, which is mainly light REEs (La-Nd). Silva *et al*. (2019) reported their pilot studies showed successful recovery with sodium carbonate leaching, and the selectivity was high towards REEs rather than calcium and iron impurities.

The Ngualla Carbonatite Complex, located close to Mbeya in Tanzania is also promising, (Witt *et al*., 2019). Despite their emphasis on primary extraction, significant amounts of waste in pre-concentrate and processing performing have continued to accumulate. Like other carbonatite systems, these residues include bastnasite and synchysite. They are friable in nature and contain low levels of thorium and hence could be considered as prime candidates of EC friendly second-generation recovery (Wang *et al*., 2020).

2.3. Central Africa

Another region of the REE-rich province is Central Africa where the Kibara Belt stretches through Burundi, Rwanda, and Democratic Republic of Congo (DRC). The belt consists of Proterozoic granites, pegmatites and metamorphic sequences that comprise allanite, monazite and zircon. In Burundi, tin and columbite-tantalite (coltan) tin mines have been discovered to have engaging amounts of the REEs, regularly as inclusions in feldspar and quartz matrices (Ntirampeba, 2020).

Even though the grades of the REE in these tailing are moderate (0.3-1.0 wt percentage TREO), they can be exploited due to the ease of access and presence of infrastructure to support small-scale reprocessing. Also, relatively low level of thorium in granitic residues decreases the necessity of strict radiological treatment, which is one of the benefits of the developing countries with weak facilities to eliminate the waste (Deng, 2020).

2.4. North Africa

In North Africa, particularly Morocco and Tunisia, lie large phosphate-bearing sedimentary basins, that are of global importance both in terms of fertilizer production and REE potential (El-Kammar, 2019). Phosphate tailings and phosphogypsum byproducts of the Moroccan mines of Khouribga and Gantour have between 400 and 1,000 ppm of REE (Liu *et al*., 2023). The REEs are found primarily as isomorphic replacement of apatite and in monazite and xenotime as individual grains.

Since Morocco is the largest producer of phosphates in the world, these wastes are an endless, huge resource (Taha *et al*., 2021). A method involving selective leaching with organic acids or ammonium sulfate solutions has proven to be effective in extracting REEs with low losses of phosphorus. The Gafsa Basin of Tunisia has some of these properties, but the tailings are not as well characterized (Khelifi et al., 2019).

2.5. West Africa

In Nigeria and Ghana, the instances of REE are largely associated with pegmatites, granites and placer (Olade, 2021). Even though there are few studies of the industrial tailings on a large scale, exploration data show possibilities in the residue of tin and columbite mining. These materials are allanite and monazite, commonly accompanied by zircon and xenotime. In Jos Plateau, Nigeria, it was studied that REE concentration can reach 0.5 wt % TREO in the weathered pegmatite tailings (Okunlola *et al*., 2022).

Although smaller than those in southern and eastern African provinces, the deposits in West Africa could be used as pilot test sites by low-cost recovery plants, especially by ion-exchange and bioleaching methods that could be adapted to artisanal conditions.

2.6. Summary of REE Distribution

Table 1 summarizes the main REE-bearing provinces, mineral hosts, and typical TREO grades based on published data from 2000–2024.

2.7. Interpretation and Implications

The amount of REE-bearing tailings in the African continent is distributed spatially with both diversity and opportunity (Abaka-Wood *et al*., 2022). Carbonatite-hosted systems (southern and eastern Africa) are the most dominant in terms of both grade and tonnes, and the granitic and phosphate deposits (central and northern Africa) are more diffuse but more extensive, (Muhindo, 2018).

Recovery wise the carbonate and phosphate structure of these tailings are favorable because they are chemically reactive, and leachable unlike refractory silicate ores (Mutimutema, 2021). The high levels of thorium deposits- like the Steenkampskraal deposits- however, need very keen radiological attention. The geography of the numerous REE tailings is favorable to pilot-scale recovery projects as many of the tailings occur near existing mining infrastructure and routes (Lindsay *et al*., 2022). The total inventory of tailings in Africa has the potential to provide a substantial portion of world REE consumption when guided through coordinated investment and technology transfer (Signe & Johnson, 2021).

Table 1: Summary of REE Distribution

Region	Major site/deposit	Dominant REE minerals	Host rock/tailings type	Typical TREO (%)	Key references
Southern Africa	Palabora, Steenkampskraal (SA)	Monazite, Bastnäsite	Carbonatite, Phoscorite tailings	0.5–1.5	Nkosi *et al.* (2022); Heikal, (2020).
Namibia	Lofdal	Xenotime, Eudialyte	Carbonatite tailings	0.4–0.8	Nkosi *et al.* (2022)
East Africa	Kangankunde (Malawi), Ngualla (Tanzania)	Bastnäsite, Monazite	Carbonatite residues	1.0–2.0	Nkosi *et al.* (2022)
Central Africa	Kibara Belt (Burundi)	Allanite, Monazite	Granitic, pegmatitic tailings	0.3–1.0	Ntirampeba, (2020)
North Africa	Khouribga (Morocco), Gafsa (Tunisia)	Monazite, Xenotime, Apatite	Phosphate tailings	0.04–0.10	Heikal, (2020).
West Africa	Jos Plateau (Nigeria)	Allanite, Zircon	Pegmatite, placer tailings	0.2–0.5	Okunlola *et al*. (2022)

Sources: Compiled and adapted from Nkosi *et al.* (2022); Ntirampeba, (2020); Heikal, (2020).; Okunlola *et al*. (2022)

3.0 Geochemistry and Hosts of African Tailings REEs

In African mine tailings, rare earth elements (REEs) are mostly hosted in phosphate, carbonate and silicate minerals found in primary deposits including carbonatites, granites and sedimentary phosphorites (Buccione, 2021). These mineral hosts and their geochemical behavior are vital to understanding how to selectively and effectively extract them. Accessibility of REE to leaching agents and their association with thorium and uranium depend on the character of the host mineral and the general environmental behavior of the residues.

3.1. Dominant Minerals of REE

Monazite

One of the most significant REE-bearing minerals of the carbonatites and the phosphate deposits in Africa is monazite [$(Ce,La,Nd,Th)PO_4$] mineral. It is commonly high in 50-70 wt% REE2O3, and is consequently very desirable to recover. Nonetheless, monazite tends to be mixed with thorium and minor uranium, which make it difficult to process and dispose of (Nkosi *et al*., 2022).

Monazite grains in tailings are usually fine-grained (10-50 µm) and embedded in gangue minerals, including quartz, barite and calcite. This encapsulation influences leachability, either it must be mechanically activated or must be pre-treated (roasted or alkaline cracked) to enhance liberation. Monazite is found as dispersed microcrystals in apatite matrices in phosphate tailings of Morocco and Tunisia and is also a source of light-REE enrichment as a whole (Heikal, 2020).

Bastnasite

Another significant REE mineral and is found in the tailings of African carbonatite, is bastnasite [$(Ce,La)(CO_3)F$], including at Kangankunde (Malawi) and Palabora (South Africa). It contains relatively less radioactive elements than monazite, and is therefore more environmentally friendly to process. Bastnasite usually has 60-70 wt% of REE_2O_3 with a light REE overload, including La, Ce, and Nd (Muhindo, 2018).

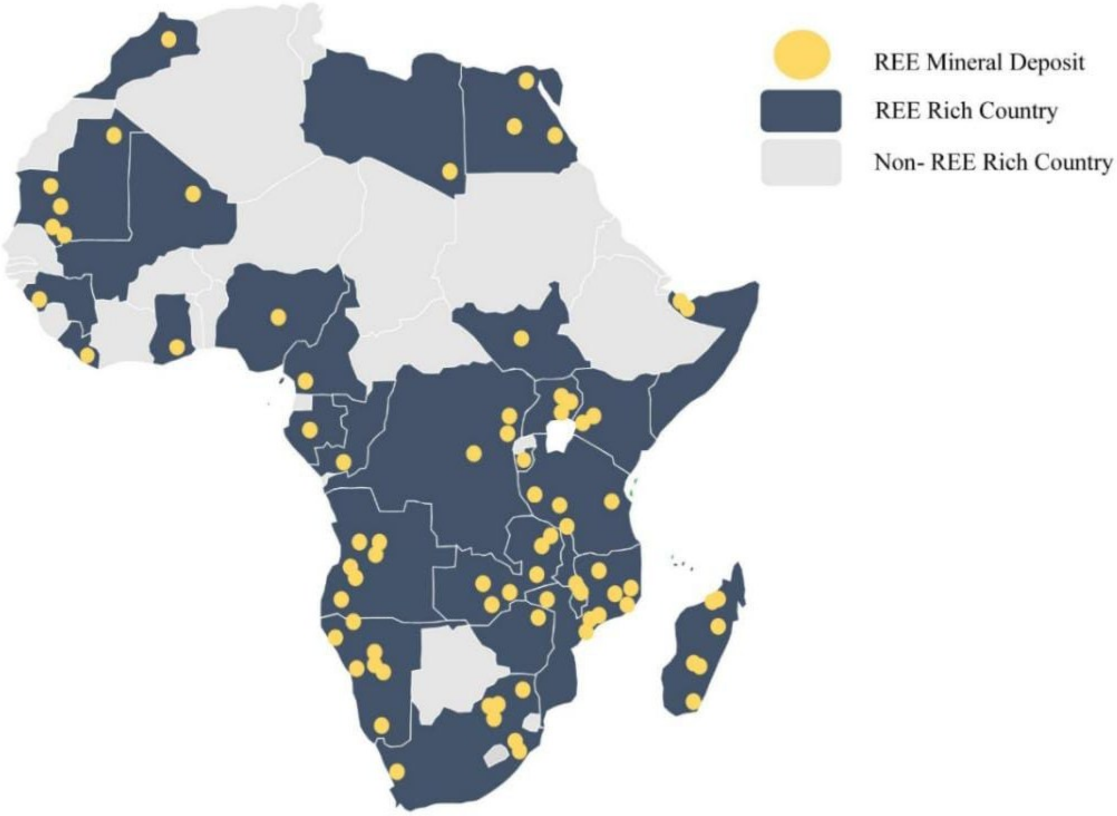

Fig. 1. Map of Africa showing major distribution of REE deposits (Bekoe *et al*., 2022).

Making it carbonate-fluoride means that it is reactive to both carbonate and acidic leaching systems. Nevertheless, due to the stability of the mineral under neutral conditions, the mineral is frequently present in the tailings over decades, which adds to the long-term supply of REE in a secondary resource.

Xenotime

The heavy rare earth elements (HREEs), including yttrium, dysprosium, and erbium, are primarily hosted in xenotime-group minerals, with the general composition [(Y,HREE)PO_4]. It is rarer than monazite or bastnasite in the African deposits, but economically valuable because of the strategic value of HREEs. Xenotime is found in Lofdal (Namibia) and the Kibara Belt (in Burundi, DRC) as discrete grains or fine inclusions in quartz and zircon.

The xenotime being a chemically resistant element tends to be concentrated in the finer fractions of mine tailings following the extraction of other soluble minerals. The leaching method is selective (e.g., using hot sulfuric acid or alkaline fusion), but on dissolution, the solutions obtained by dissolving xenotime contain high-purity HREE oxides (Heikal, 2020).

Allanite

Allanite is an epidote, [$(Ce,Ca,Y)_2(Al,Fe^{3+})_3(SiO_4)_3(OH)$] silicate REE host. It is common in granitic and metamorphic formations of central and western Africa, particularly Kibara Belt and Jos Plateau. Even though the REE concentration in allanite bearing tailings tends to be lower (0.3-0.8 wt% TREO), the high tonnages of the pegmatite and feldspathic residues make them a viable economic consideration (Ntirampeba, 2020). The complex silicate structure of allanite causes difficulties in extracting the REE, and in many cases, high-temperature alkaline digestion is necessary. Nevertheless, it is possible to increase its reactivity through partial weathering in tropical climates, which can justify the moderate yields of extraction in tailings in West Africa.

3.2. Phases and Adsorbed Forms of Secondary REE

Besides the major REE minerals, some African tailings deposits do include secondary REE-bearing minerals developed through weathering or mineral treatment. These include:

i. Under oxidizing conditions bastnasite is transformed into REE-oxides and hydroxides;
ii. REE-carbonates deposited in the neutralization of tailings; and
iii. REE species attached to clay minerals such as kaolinite and smectite as in ion-adsorption clays of southern China, but ion-adsorbed (Heikal, 2020).

Though the ion-adsorbed REEs in Africa are found in low concentrations, their occurrence denotes a possibility of low-cost recovery with ammonium sulfate or mild leaching systems. This point should be investigated more, in particular, in weathered carbonatite tailings where the formation of clay is frequent.

3.3. Geochemical Associations

Phosphorus (P_2O_5) and fluorine (F) in phosphate-enriched tailings, or calcium (Ca) and barium (Ba) in carbonatite-associated tailings are often strongly correlated with the REEs in tailings. These associations affect the extraction behavior and the stability of the environment.

i. Phosphate minerals are easily dissolved in acidic systems to release REEs and thorium concomitantly.
ii. Under slightly basic conditions, REEs are dissolved in carbonate systems rich in carbonates, allowing them to be selectively leached with either $NaCO_3$ or $H_2O_2CO_3$.
iii. REEs in silicate systems are firmly held in crystal structure and will only dissolve under harsh conditions like roasting or fusion.

REE mobility is also influenced by the redox status of the iron and manganese oxides in the tailings. Fe^{3+} oxides can absorb REE ions in the oxidizing conditions, forming a secondary enrichment area in tailings impounds (Muhindo, 2018). On the other hand, at reducing conditions, REEs are not mobile, resulting in vertical zonation of the REE concentrations in old tailings piles.

3.4. REE Fractionation Patterns

Multiset of African deposits geochemical analyses show a different pattern of light (LREE) and heavy (HREE) fractionation.

i. The tailings of carbonatites (e.g., Palabora, Kangankunde) are dominated by light REEs including La, Ce and Nd.
ii. Tailings of granitic and pegmatitic iron ores (e.g., Burundi, Nigeria) exhibit middle to heavy REE (Sm-Er) enrichment.
iii. The balanced REE patterns of phosphate deposits (e.g., Morocco, Tunisia) indicate a sedimentary origin as well.

Patterns of chondrite-normalized REE in these tailings are often strongly light-REE-enriched (La/YbN > 50) and variable Eu, suggesting that they were fractionated by hydrothermal alteration and then reverted to their original state through weathering (Heikal, 2020). Such geochemical diversity means that the tailings in Africa have light and heavy recovery of REE, which can be used to support diversification of the products portfolio.

3.5. Mineralogical Processing Problems

The rich mineralogy of African tailings presents a number of challenges in processing:

i. Particle size of fine particles – Tailings generally have a size of less than 75 µm, limiting the efficiency of the flotation process and making separation between solid and liquid difficult during the leaching process.
ii. Mixed mineral associations – Monazite and bastnasite are usually associated with barite, fluorite, and calcite, which are acid consuming and reduce selectivity.
iii. Radioactivity contaminants – Thorium and uranium in monazite imagine radiological safe measures and regulated management of residues.
iv. Diversity of the REE distribution – REE content in tailings ponds may differ greatly even within the same

deposit because of different methods of processing in the past.

To solve these problems, mineralogical characterization with X-ray diffraction (XRD), scanning electron microscopy (SEM), and inductively coupled plasma mass spectrometry (ICP-MS) is necessary prior to the design of recovery processes (Balaram, 2023). Combined mineralogical and geochemical data allow to choose the necessary leaching systems: phosphates are in favor of acid leaching, silicates of alkaline leaching, carbonatites of carbonate leaching.

4.0 Extraction and Processing Methods

The extraction of rare earth elements (REEs) out of mine tailings is largely based on the choice of appropriate extraction and processing technologies compatible with the mineralogical properties of the residues (Hidayah, & Abidin, 2018). Since tailing of African mines are highly diverse, in the form of phosphate-rich material, carbonatite and granitic deposits, various leaching and purification techniques are needed. Hydrometallurgical methods, especially selective leaching, solvent extraction, and ion exchange, are the most promising because they have relatively low energy requirements and can be adapted to small- and medium-scale operations.

4.1. Summary of REE mining chemistry

The main factor affecting extraction chemistry is the chemical composition of the REE-bearing minerals.

i. Monazites and xenotimes are phosphate minerals resistant to direct attack by acids, except when pretreated by roasting or cracking.
ii. Carbonate minerals such as bastnasite are easily dissolved by both acidic and carbonate solutions.
iii. Allanite is a more refractory silicate mineral that alkaline digestion.

The aim of extraction is to preferentially dissolve REEs without extensively dissolving impurities like Fe, Ca, and Al, which might complicate subsequent separation (Nkosi *et al*., 2022).

4.2. Acid Leaching

4.2.1. Sulfuric Acid Leaching

Dissolution of REE in sulfuric acid (H_2SO_4) is among the most frequent dissolution reagents, given its low cost and high performance. Monazite-bearing tailings research has demonstrated that in South Africa, the Steenkampskraal and Palabora complexes can be subject to leaching at 2-3 M H_2SO_4 and 150-200 °C to recover >90% of the REE (Nkosi *et al*., 2022).

The process of reaction consists of dissociation of REE-phosphate bonds to give soluble REE sulfates:

$$2(REE)PO_4 + 3H_2SO_4 \rightarrow (REE)_2(SO4)_3 + 2H_3PO_4$$

Yet, thorium and uranium are also solubilized in this process and must be further refined or neutralized carefully in order to clear radioactive impurities. Process optimization typically involves staged leaching and residue washing to minimize the waste acid discharge.

4.2.2. Hydrochloric Acid Leaching

Hydrochloric acid (HCl) leaching is more selective of light REEs and better extracted downstream, because of chloride complexation. Khelifi *et al*., (2019) listed 80-95% phosphate tailings extraction efficiency in Morocco with 4 M HCl at 80 °C. In spite of its efficiency, HCl leaching presents increased corrosion risk and operation costs. Recycling in a closed-loop system, however, is a possibility with acid regeneration of calcium chloride by-products.

4.2.3. Nitric Acid Leaching

Nitric acid (HNO_3) has cleaner leach solutions and fewer impurities however it is not as common because it is more expensive and is an oxidizing agent. Moderate (~75 %) recoveries on limited trials in the Kangankunde tailings in Malawi at high reagent consumption were observed (Mutimutema, 2021). Nitric systems can be more adept at laboratory-scale separations or selective stripping in solvent extraction than bulk leaching.

4.3. Alkaline and Carbonate Leaching

4.3.1. Alkaline Digestion

Monazite bearing tailings are especially effective with alkaline leaching using sodium hydroxide (NaOH) or sodium carbonate (Na_2CO_3). The reaction transforms REE phosphates to soluble hydroxides or carbonates and thorium is insoluble and precipitates as ThO_2:

$$REEPO_4 + 3NaOH \rightarrow REE(OH)_3 + Na_3PO_4$$

This method has been successfully tried at the Kangankunde pilot plant in Malawi, where the recovery of 85-90% REE with a low radiation view was observed (Mutimutema, 2021). Reagent recycling is also easier and acid waste is reduced in alkaline processes. These however, have higher operating temperatures (120-150 °C) and have to be carefully maintained to avoid sodium accumulation in circuits.

4.3.2. Carbonate Leaching

Sustainable alternatives have come in the form of carbonate leaching systems with either ammonium bicarbonate (NH_4HCO_3) or ammonium sulfate (($NH_4)_2SO_4$. These reagents extract REEs selectively in mild conditions (pH 7-8, 50-80 °C). The resulting carboxylates of REE-carbonates can be readily reduced to oxides by heating.

$$REE_2(CO_3)_3 + 900^oC \rightarrow REE_2O_3 + 3CO_2$$

Carbonate leaching reduces the dissolution of thorium and is consistent with low-impact processing appropriate to African pilot plants (Heikal, 2020).

4.4. Green Chemistry and Bioleaching

Biological leaching provides an ecologically friendly and cost efficient alternative. Organic acids (citric, oxalic, gluconic) capable of dissolving REE in tailings can be produced by microorganisms (e.g., Acidithiobacillus ferrooxidans) and by fungi (e.g., Aspergillus niger) (Mutimutema, 2021). In laboratory tests of South African and Namibian tailings, bioleaching recovered between 60 and 70% of the REE in 10-14 days at ambient conditions. Slower than chemical leaching, bioleaching requires fewer reagents and produces less waste. Furthermore, it is applicable to small or remote Africa operations that have a small chemical supply chain.

Recent research has investigated also the new leaching agents in terms of deep eutectic solvents (DES)-green solvents that are made up of all-organic biodegradable substances. Other systems like choline chloride-urea and choline chloride-glycerol have been highly selective to Nd^{3+} and Dy^{3+} ions without the presence of thorium (Rudney, 2020). These methods would be the basis of the future green metallurgy projects in Africa.

4.5. Recovery and Purification

Once they have been leached, the solutions that contain REE need purification and separation into separate oxides or salts. Primarily, downstream methods are:

4.5.1. Solvent Extraction

The industrial method of REE separation is solvent extraction (SX). D_2EHPA (di-(2-ethylhexyl)phosphoric acid), Cyanex 272, and PC-88A are examples of common extractants that selectively transfer REEs between aqueous and organic phases. On African continent, those at Steenkampskraal and Lofdal have established recoveries of over 98% REE purity (Heikal, 2020). Multi-stage countercurrent SX systems can allow effective light and heavy REE fractionation, but infrastructure and trained operators are needed.

4.5.2. Ion Exchange

Dilute REE leachates are useful in processing with ion exchange resins, especially those resins with functional phosphonic or aminophosphonate groups. These resins are very selective in trivalent REE ions, and can be easily regenerated. It is less capital intensive than solvent extraction and is therefore appealing to smaller African facilities (Heikal, 2020).

4.5.3. Calcification and Precipitation

The last stage is to precipitate REEs as oxalates or carbonates, and then to heat them to get high-purity oxides of REEs:

$$2REE^{3+} + 3C_2O_4^{2-} \rightarrow REE_2(C_2O_4)_3$$

$$\downarrow$$

$$REE_2(C_2O_4)_3 + 900^oC \rightarrow REE_2O_3 + 3CO_2 + 3CO$$

This is also the path that has been being tested in the pilot projects conducted in Namibia, where solar-assisted kilns are offered as sources of sustainable heat (African Development Bank, 2024).

4.6. Process Integration and Optimization

Integrating leaching, recovery, and purification steps into a continuous circuit improves efficiency and reduces waste. A simplified flowsheet (Fig. 2) illustrates the recommended pathway for African tailings:

(i) Tailings conditioning and particle sizing
(ii) Selective leaching (acidic, alkaline, or carbonate)
(iii) Solid–liquid separation
(iv) Solvent extraction or ion exchange
(v) Precipitation and calcination
(vi) Residue stabilization and water recycling

Each stage can be adapted to local conditions, reagent availability, and energy costs. For example, solar-assisted evaporation and locally produced organic acids can significantly reduce operational expenses in regions with limited access to imported chemicals.

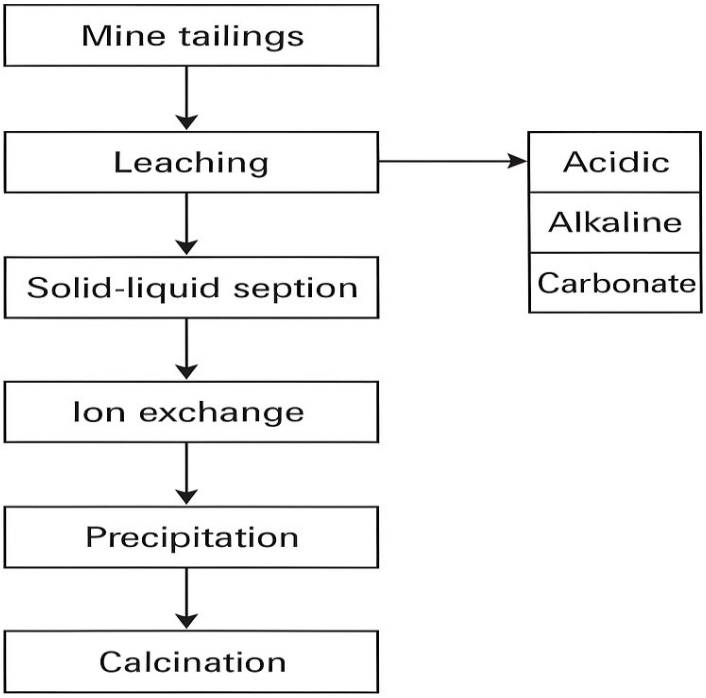

Fig. 2. Comparative Efficiency of Leaching Systems

4.7. Process Performance and Continuous Improvement

A continuous circuit is much more efficient and produces smaller waste by combining leaching, recovery, and purification processes into a longer circuit. The possible pathway that should be taken by African tailings is shown in a simplified flowsheet (Fig. 2):

i. Particle sizing and tailings conditioning.
ii. Selective leaching (acidic, alkaline or carbonate)
iii. Solid-liquid separation
iv. Solvent extraction or ion exchange.
v. Precipitation and calcification.
vi. Water recycling and stabilization of residue.

The individual stages are changeable to local circumstances, reagent accessibility, and energy prices. Solar-assisted evaporation, the use of locally available organic acids, and some facets of solar panels can greatly lower costs of operation in areas with scarce access to imported chemicals.

5.0 Economic and Environmental Viewpoints

The reuse of African mine tailings to recover rare earth elements (REEs) presents a rare chance to meet two long-standing challenges of the mining industry, environmental rehabilitation and resource diversification. The impact of traditional REE mining is frequently viewed negatively due to its environmental footprint and radioactive wastes, whereas tailings reprocessing offers a less impactful route enabling the transformation of current liabilities into economic benefits. However, to achieve these advantages, the waste management, water consumption, and the financial aspects of doing business in developing countries need to be taken into consideration.

5.1. Environmental Considerations

5.1.1. Radioactivity Management and Thorium

Thorium (Th) and minor uranium (U) is also one of the major environmental issues in the REE recovery, especially through the monazite-bearing tailings. These constituents occur in the form of natural impurities in REE minerals which can be radiologically hazardous unless well managed. South African and Namibian tailings can contain up to 0.3 wt% ThO_2, which requires measures to handle and dispose of safely (Nkosi *et al.*, 2022).

This is taken care of in modern hydrometallurgical processes, which precipitate thorium as $Th(OH)_4$ or ThO_2 during an alkaline treatment, thus effectively immobilizing the radioactive element. The cementitious or geopolymer matrices can then encapsulate the precipitate, minimizing leachability and radiation exposure (Nkosi *et al.*, 2022). These stabilization methods are in line with global best practice and can be adapted to African industrial standards.

5.1.2. Water Recycling and Reagent Recycling

Hydrometallurgical processes cause high levels of water and other reagents which can be of concern when the geographical areas are dry and may be costly to procure water and other reagents. But generally REE tailings recovery circuits can be pitched to closed-loop water recycles which reuse neutralized and filtered process water.

Pilot operations in Malawi have shown up to 90 percent recovery of water under lime-based neutralization and sedimentation. Also, some reagents, including sulfuric acid or ammonium sulfate may be recycled or reused, by a simple distillation or crystallization process, decreasing environmental effects, and operation costs (Signé, & Johnson, 2021). Solar assisted evaporation pond or reverse osmosis systems may also be installed in areas rich in solar energy to enhance water management further.

5.1.3. Tailings Rehabilitation

Legacy mine sites can also reuse the reprocessing of tailings. After removing valuable materials, the left residues may be neutralized, compressed, and surrounded by soil or vegetation to minimize dust and soil erosion. According to some studies, they recommend that the treated residues should be used as aggregates in construction materials, including bricks or cement, as long as radiological concentrations are not excessively high (Nkosi *et al.*, 2022).

This strategy favors the mine-to-materials circular concept, with waste in one process becoming input to another, which is a long-term way to achieve environmental sustainability.

5.2. Economic Viability

5.2.1. Capital and Operating Costs

In most cases, the cost of reprocessing tailings is less than that of new mining ore since the comminution and primary beneficiation have already been carried out. The primary cost activities include reagent turnover, energy needs, and chemical purification. The African Development Bank (2024) estimated that reprocessing would cost between 25 and 40 tonnes of tailings depending on mineralogy and the complexity of the process. The economic models that have been developed to design REE in South Africa, Malawi and Morocco indicates that to make certain projects profitable, it is important to have a total rare earth oxide (TREO) of more than 0.5 wt% and a recovery efficiency of above 70%. With the estimated market prices of 2024 of Nd_2O_3 of $110/kg and Dy_2O_3 of $370/kg, even considering the cost of reagents and energy, recovery of the REE can give net revenues of between $500 and 1000 per tonne of treated tailings.

5.2.2. Market Volatility and Risk

In spite of promising economics, REE markets are volatile due to geopolitical and technological factors. Any variation in REE prices can have a substantial impact on the net present value (NPV) of recovery projects ranging between +-30%. African producers may also strive to alleviate those risks by taking advantage of multi-products recovery, not only recalling REE, but also finding by-products in the tailings like a barite, fluorite, or phosphate fertilisers. Moreover, cooperation at the regional level can increase bargaining power, decrease export dependence, and accelerate the creation of local value chains in magnet and battery materials, such as the African Continental Free Trade Area (AfCFTA).

5.2.3. Infrastructure and Energy

An important factor that determines the feasibility of a project is the availability of energy. Most of the processes involved in REE recovery demand ongoing heating or electrical leaching, separation, and calcination. Countries like Namibia, Botswana and South Africa, which have stable power supply and expanding renewable resource base are ideally placed to use REE tailings. Where the power supplied by grid is insufficient, additional power can be supplied by solar-powered or biomass-powered systems. The pilot project of solar-assisted calcination in Namibia shows how renewable energy can help decrease CO2 emissions and lower operational expenses by up to 15 percent (African Development Bank, 2024).

5.3. Policy and Regulatory Frameworks.

5.3.1. African Mining Vision (AMV)

In 2009, the African Mining vision (AMV) was endorsed by the African Union, with an emphasis on value addition, resource efficiency and local beneficiation. The recovery of the tailings follows these principles directly as it enhances sustainable utilisation of the mineral resources and reduces wastage. The AMV offers a policy basis to incorporate the concept of REE recovery into the wider industrial development packages (UNECA, 2020).

5.3.2. Radiation Safety Environmental Legislation.

In some countries such as South Africa, Namibia and Malawi, national environmental legislation has already been enacted obligating impact assessment and monitoring of radiations in mineral development projects. There is, however, wide implementation and enforcement. It would also increase uniformity and investor confidence by establishing regional standards to manage thorium as is done by the International Atomic Energy Agency (IAEA). Moreover, the benefits of public-private partnerships (PPP) can be used to finance pilot-scale plants, educational opportunities and development of laboratories, so that local expertise is increasing pace with industrialization.

5.3.3. Socioeconomic Benefits

Restoration of tailings creates jobs and fosters skills development within the fields of mineral processing, chemical engineering, and other aspects of environmental management. The potential project sites are mostly concentrated around rural or semi-urban settlements where new economic activities will help in developing the local settlement. Moreover, social license to operate can only be sustained through community participation and effective message delivery, particularly in cases where the materials in question are characterized by radioactive elements.

5.4. Circular Economy Perspective and Sustainability

Reprocessing of REE-bearing tailings is an example of the principles of the circular economy, which tries to keep material value and reduce wastes. Through resource recovery of REEs in the remnants, the mining industry can shift to zero-waste-production and promote decarbonization. It is estimated that every tonne of REE oxide extracted in tailings will help prevent 9-12 tonnes of CO2 equivalent emissions relative to primary mining (Buccione *et al*., 2021). Moreover, simultaneous application of renewable power sources with water recycling and use of by-products can make REE recovery facilities green refineries. Such initiatives not only make Africa a leading nation in sustainable management of resources but also minimises environmental liabilities (Samakinde *et al.*, 2023).

6.0 Future Prospects and Future Challenges

The world is moving towards clean energy and digital technologies which have created a massive demand on rare earth elements (REEs). Evs, wind turbines and other high tech electronics rely on REE based materials like neodymium-iron-boron (NdFeB) magnets and phosphors. In the case of Africa, with the increased value of REEs, this poses both a strategic and a technological challenge. New, sustainable REE industry could be based on the vast tailings deposits found on the continent, containing most of the REE-bearing minerals. But, the key will lie in the ability to break through obstacles in technology, finance, infrastructure, and governance.

6.1. Technical Developments and Research.

6.1.1. Processing of Mineral Innovations

African tailings are diverse, with gradual-grained blends of carbonates, phosphates and silicates. The future lies in the realization of selective lowcost mineral processing technologies that can be used to treat mixed noble mineral assemblage. New studies are developing regarding:

i. Microwave-assisted leaching, occurring when microwave heats minerals, boosting their dissolution speed and reducing the amount of acid consumed to as much as 40% (Mutimutema, 2021).
ii. The process that converts bastnasite and monazite tailings targets supercritical CO2 carbonation, to convert the REEs into soluble complexes in mild conditions. Electrochemical and plasma-assisted leaching which provide reagent-free alternatives decreasing the wastes produced.

These innovations would support the viability of reprocessing small decentralized African facilities in which the logistics of reagents is a bottleneck.

6.1.2. Circular Processes and Biohydrometallurgy

New technologies includes bioleaching, biosorption, and biomineralization, suitable to warm climates and rich biomass resources of Africa. Native microbial communities can be utilized to extract REE in tailings at close-to-ambient conditions using low levels of chemicals. South African carbonatite tailings were pre-tested with Acidithiobacillus ferrooxidans and Aspergillus niger with 60-70% of REE recovery after 2 weeks (Mutimutema, 2021).

Subsequent studies must be aimed at streamlining microbial strain selection, biofilm management, and scale-up considerations in continuous bioreactors. REE recovery could be made completely circular, with integration into waste-to-resource systems including the generation of organic acids out of agricultural byproducts.

6.1.3. Process Modeling Digitalization

Leaching and separation parameters can be optimized by implementing digital technologies, including machine learning (ML), geometallurgical modeling, and artificial neural networks (ANN). By using machine learning (ML) algorithms, REE recovery efficiencies may be estimated using mineralogical and chemical datasets, thus decreasing the use of large bench testing. Indicatively, initial applications of Namibian and Malawian deposits in data-driven simulations have already shown the correct kinetics of REE leaching could be predicted, and process design could be customized prior to piloting (Mutimutema, 2021). The creation of African databases on tailings composition and REE mineralogy at a centralized location would facilitate cross-country benchmarking and cooperation.

6.2. Policy and Institutional structures.

6.2.1. Enhancing Regional Cooperation

The wide spread of REE-bearing tailings throughout the African continent is an opportunity to practice regional specialization. Southern Africa may concentrate on those REEs that occur in carbonatites, North Africa on phosphate based stricties, and Central Africa on granitic and pegmatitic sources. The African Mining Vision (AMV) of the African Union and AfCFTA may serve to facilitate cross-border cooperation in research, processing, and marketing (UNECA, 2020). Technical training, pilot-scale testing and transferring technology would be easier by creating African Rare Earth Centres of Excellence, perhaps at the University of the Western Cape, or the University of Namibia.

6.2.2. Drawing in Investment and Infrastructure Development

Although geology is promising, there is little individual investment in the African REE industry owing to the perceived political and financial risks. Governments can deal with this by:

i. Consistent regulations on tailings ownership and environmental liability.
ii. Green processing technologies that have tax benefits and feed-in tariffs.
iii. The development of renewable energy systems and reagent production facilities as public-private partnerships (PPP) to share the burden.

These would make Africa a more attractive place to invest in sustainably and provide an alternative to conventional producers of REE.

6.2.3. Governance and Transparency

Good governance and transparency are the keys to investor and community confidence. Traceability systems on REE products - akin to those employed by conflict mineral supply chains - can help ensure that recovered materials have reached ethical and environmental standards. The online tracing of batches of REE found in tailings to export may increase market confidence and promote integration into global supply chains.

6.3. Local Value Addition and Economic Diversification

Historically, African economies have depended on the export of raw or semi-processed minerals and much of their value is lost to foreign industries. REE tailings reprocessing is an opportunity to turn this direction and encourage local beneficiation.

i. Step 1 Recovery of mixed REE concentrates in tailings.
ii. Step 2: Purification to single oxides and compounds (Nd_2O_3, Dy_2O_3, etc.).
iii. Step 3: REE-based components like magnets, catalysts and phosphors are fabricated in Africa.

Even creating modest downstream capability, like to produce magnet alloys, could raise export prices more than 300 percent higher than raw oxide sales (African Development Bank, 2024). Regional manufacturing and employment would also be induced through the establishment of REE industrial belts around mining centres such as Johannesburg, Windhoek and Lilongwe.

6.4. Environmental and Social Governance (ESG) Priorities.

The development of the Africa REE strategy should be framed around sustainability. This means embracing Environmental, Social and Governance (ESG) principles throughout:

i. Inclusion of community and open market benefit sharing.
ii. Measuring a radioactivity and the quality of water to meet international safety standards.
iii. Enhancing women and youth participation in technical and managerial positions.
iv. Promoting the integration of indigenous knowledge particularly in the rehabilitation of the environment.

By complying with the best practices of ESG, Africa will increase its competitiveness and access to “green financiers like climate funds and sustainable mining bonds.

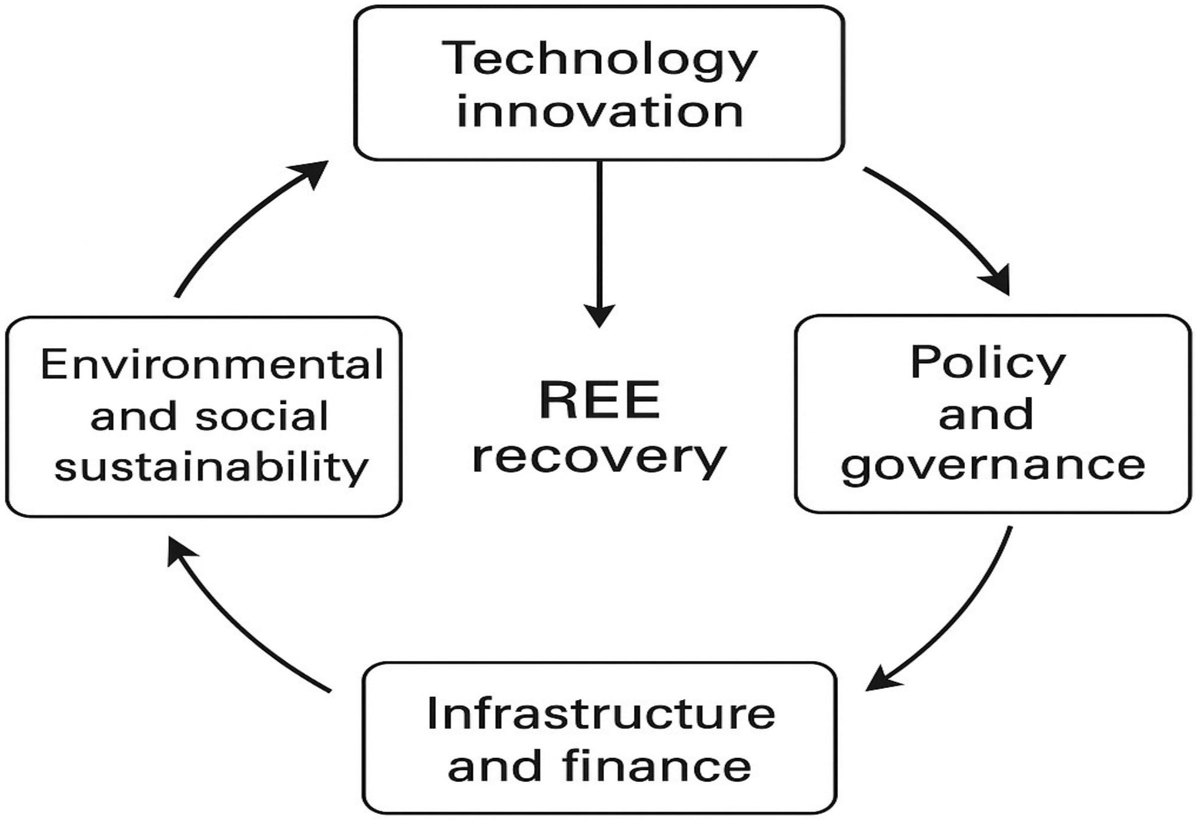

Fig. 3. Integrated framework linking technology, policy, and sustainability for REE recovery from African mine tailings.

6.5. Challenges to Overcome

Nevertheless, there are still a few challenges, including:

i. Technological constraints -Majority of African countries do not have dedicated REE processing units and human resources.
ii. Funding factors - Costs are high and less predictable prices in the market are a constraint to involvement in the sector by the private sector.
iii. Infrastructure issues - The distribution of power, the transportation of reagents and laboratory capacity are disproportionate.
iv. Asymmetry of regulations - Differences between environmental and mining regulations among countries stand in the way of integration.
v. Radiation issue and public perception - There is historical stigma about the use of radioactive minerals which tends to hold-up project passes.

To overcome these obstacles, governments, research institutions, and private investors will need to work in coordination with international collaborations.

6.6. Outlook

Africa may take a step forward in the international REE supply chain in the next decade. REE extraction out of tailings will become more and more possible with technological advances in green metallurgy, computer-controlled processes, and the construction of the circular economy. With the right kind of regional cooperation, open governance, and targeted investments, Africa has the potential of becoming a viable REE source, both in terms of light and heavy-weight REEs, and in terms of restoring its mining terrains. If, as a strategy to turn waste into strategic resources, the REE tailings in Africa are used not only as an engine of economic growth, they can also depict Africa as an innovator and survivor amid the world resource crisis.

7.0 Conclusion

Potential solutions to the shortage of mine tailings in Africa are found in the recovery of rare earth elements (REEs) which offer a transformational direction to the mining and resource sectors in Africa as shown in Fig. 3. The continent is home to diverse deposits of both light and heavy REEs with the presence of numerous systems (carbonatites, granitic, and phosphates) that all bear large amounts of the elements. These tailings which have been considered as waste since ancient times form an underutilized second source that can play a significant role in global supply chains and reducing the environmental effects of past mining.

The main REE minerals that were found in the African tailings are monazite, bastnasite, xenotime, and allanite, which indicates the diversity of the continent. Light REEs are common in the carbonatite provinces of the southern and eastern African regions and the heavy REEs are found in the granitic and sedimentary systems of the central and northern regions. The geochemical behavior of these minerals is always important in the design of selective and efficient mining systems.

Hydrometallurgical treatments - acidic, alkaline, and carbonate leaching [with solvent extraction and ion exchange] have been found to hold good potential in the recovery of REE. Simultaneously, other sustainable substitutes such as bioleaching and deep eutectic solvents are coming into play as an option that is feasible with limited impact on the environmental and energy situation in Africa. These technologies can be combined in a modular and closed-loop circuit in order to make them efficient and produce less waste.

Tailing reprocessing does not only recover useful elements, but it also stabilizes the radioactive residues, cuts down on the water and dust pollution, and reinstatement of damaged mine locations. It is economically favourable (enabling employment, benefiting the locals, adding value), which is in line with the African Mining Vision (AMV) and AfCFTA frameworks (sustainable industrialization and regional collaboration).

Nevertheless, technological capacities, poor infrastructure, unstable laws and unstable markets are some of the key impediments. To overcome these challenges, there is a need to invest long term, collaborate with researchers, build capacities and harmonization of regulatory standards.

Finally, through sustainable recovery of REEs, environmental liabilities can be converted to strategic resources to promote circular, inclusive and climate resilient mineral development. Africa can become a responsible global source of vital materials to clean energy transition through innovation, good governance and regional collaborations.

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