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Review

From Waste to Wealth: A Circular Economy Approach to the Sustainable Recovery of Rare Earth Elements and Battery Metals from Mine Tailings

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Abstract: The increasing global demand for critical minerals, driven by rapid population growth and the widespread adoption of low-carbon technologies, electric vehicles, and clean energy systems, highlights the urgent need for sustainable resource management. Mine tailings, traditionally considered waste, are now being recognized as valuable secondary sources for mineral recovery. This paper compiles a comprehensive review of the four short- and mid-term critical minerals (lithium, cobalt, nickel, and rare earth elements) and provides insights regarding their recovery with a focus on the latest technological advancements. By exploring key innovations in separation processes, the review demonstrates how these technologies are addressing supply chain bottlenecks while simultaneously reducing the environmental footprint of mining operations. The paper also advocates for a holistic approach to mine waste management, integrating mineral recovery with environmental remediation. It emphasizes the dual benefits of recovering valuable resources while purifying contaminated water and mitigating pollution risks. The proposed circular economy model suggests a sustainable blueprint for managing mine tailings, emphasizing resource reuse, waste reduction, and economic viability.

Keywords: critical minerals; mine tailings; mineral recovery; circular economy flow

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1. Introduction

Critical minerals are indispensable for advancing clean energy technologies and manufacturing essential products like electric vehicles, smartphones, and renewable energy systems. Their importance stems from their role in enabling the transition to a low-carbon economy by supporting the development of key components such as batteries, magnets, and catalysts for energy storage and clean energy generation. Despite the abundance of critical minerals in the lithosphere, concentrated deposits are located only in a few countries, creating significant geopolitical complexities and supply disruptions due to trade regulations [1,2]. For example, while China has been the leading producer of 29 distinct raw metals, including molybdenum (Mo), vanadium (V), tungsten (W), aluminum (Al), arsenic (As), and rare earth elements (REEs), the USA heavily relies on imports, being 100% dependent on foreign sources for 12 critical minerals and over 50% reliant on 31 others [3–5]. This underscores the need for diversified supply chains and investments in exploration and production.

Mining and mineral processing generate vast quantities of tailings, which contain residual metals formed through chemical and mechanical processes [6]. These tailings,

often stored in ponds, can adversely impact geochemical environments, water quality, and biodiversity [7]. However, reprocessing tailings offers a dual benefit: providing a sustainable supply of critical minerals while mitigating environmental contamination and stabilizing hazardous materials. Countries with abundant critical mineral deposits, such as China, Australia, and Canada, leverage their resources to influence global supply networks. Similarly, emerging economies like Indonesia, Nigeria, and Namibia are emphasizing their strategic mineral reserves to support the low-carbon transition. These dynamics highlight the critical role of resource management in shaping geopolitical and economic power [8]. In response to growing risks in critical mineral supply chains, international collaboration is expanding, focusing on diversifying sources, enhancing competitiveness, and addressing social and environmental challenges, particularly in developing nations. Figure 1 illustrates the leading countries in critical mineral production for 2023 including recycled metals.

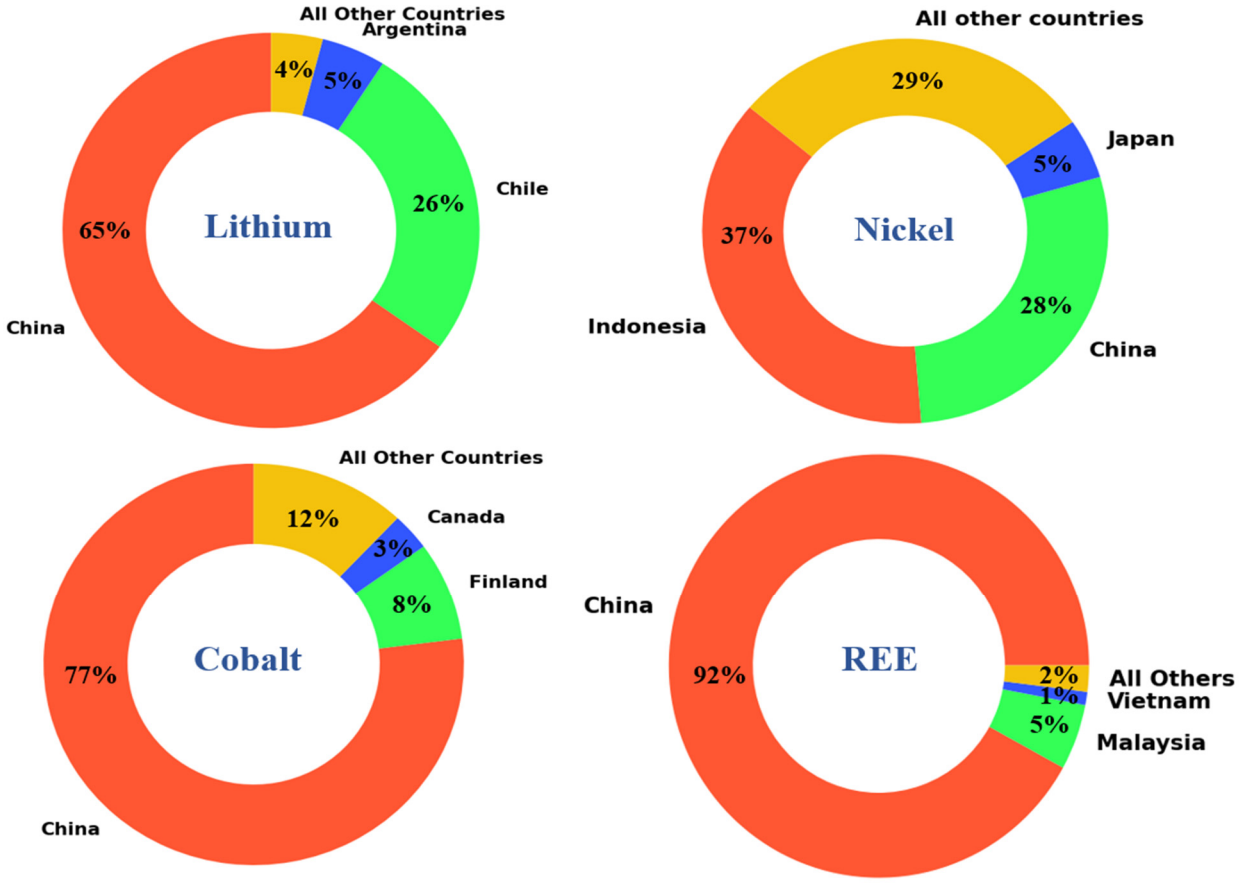


Figure 1. Countries leading the production of critical minerals in 2023 [9].

Figure 2 shows mineral criticality matrix published by the USA's DOE NETL for short- and mid-term goals based on the USA's national priorities, often considering the needs of strategic industries like defense, information technology, and renewable energy. Short-term criticality typically encompasses a time horizon of one to five years and focuses on immediate supply–demand risks driven by sudden economic, geopolitical, or technological changes. Key factors contributing to short-term criticality include rapid advancements in industrial sectors, such as electric vehicles and renewable energy technologies, as well as supply chain vulnerabilities arising from geopolitical tensions or trade restrictions. The lack of scalable substitutes or recycling capacity for certain critical minerals exacerbates these short-term risks. Mid-term criticality, on the other hand, typically spans a time horizon of five to ten years and emphasizes strategic planning to address projected industrial growth and evolving supply chains. Determinants of mid-term criticality include long-term trends

such as the global adoption of renewable energy technologies, decarbonization targets, and the development of next-generation energy storage solutions. For this paper, rare earth elements, lithium, cobalt, and nickel were selected for further review due to their short- and mid-term high criticality. This review paper addresses the existing knowledge gap by presenting a comprehensive overview of selected critical minerals found in mine tailings and exploring the latest advancements in separation technologies that have significantly improved the efficiency of mineral recovery. A critical component of this paper is the development of a circular economy model that highlights the sustainability and economic importance of recycling mine tailings. This model emphasizes resource reuse, waste reduction, and best practices for tailing management, offering a sustainable blueprint for integrating mineral recovery with environmental remediation. Beyond the technical scope, this review advocates for a holistic approach to tailing management, focusing on the dual benefits of extracting valuable resources while mitigating environmental risks.

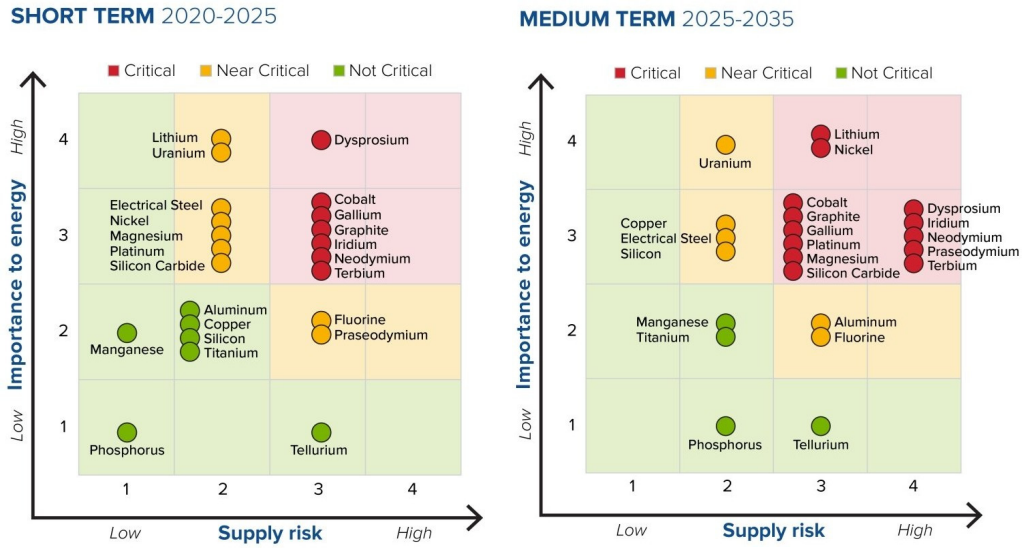


Figure 2. Mineral criticality matrix [10].

2. Selected Critical Minerals for Further Review and Their Recovery Methodologies

2.1. Lithium

Lithium, a silvery alkali metal known for its softness, has emerged as a critical mineral due to its extensive use in lithium-ion batteries (LIBs), which dominate the energy storage market for electric vehicles (EVs) and portable electronics [11–13]. LIBs have gained prominence for their high specific capacity, memory-free operation, exceptional cycling performance, minimal self-discharge, and broad operating temperature range, making them integral to clean energy and technology sectors [14,15]. The demand for lithium in EVs alone has risen substantially, from 34.6 kt in 2015 to 49.0 kt in 2019 [11,16,17]. Recent data (Figure 3) indicate a notable shift in lithium consumption patterns. In 2017, 30% of lithium production was utilized in clean energy applications, a share that grew to 56% by 2022. Concurrently, the energy transition minerals market expanded to USD 320 billion in 2022, driven by a 30% increase in critical mineral development and a 20% rise in lithium exploration. This growth was further supported by record-breaking venture capital funding for critical mineral startups, which totaled USD 1.6 billion—4% of all clean energy investments [18].

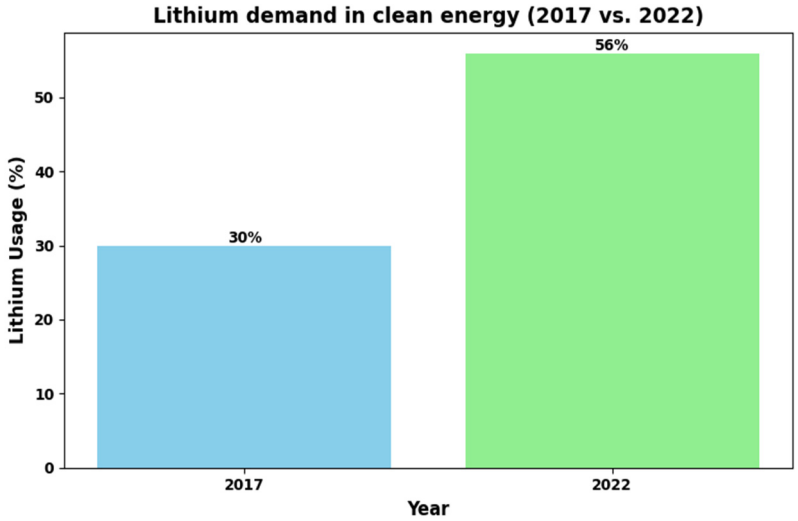


Figure 3. Lithium demand in clean energy in 2017 and 2022 [18].

Lithium is abundant in nature, but economically mineable reserves are limited. Its primary sources include brine salt flats and pegmatite—a granitic rock containing lithium-rich minerals such as spodumene, lepidolite, petalite, and zinnwaldite [19]. The "Lithium Triangle", encompassing Argentina, Chile, and Bolivia, holds nearly 50% of global lithium deposits, with concentrations ranging from 1000 to 3000 ppm. Outside this region, Australia, Brazil, Canada, China, Portugal, and Zimbabwe dominate pegmatite-based lithium production while China and the USA lead lithium extraction from brines [20]. In the USA, significant lithium deposits include the Kings Mountain pegmatite area in North Carolina and the Thacker Pass hectorite deposit in Nevada, each estimated to contain 5.9 million metric tons [21]. However, the variability in lithium content, dictated by the deposit type, geology, and extraction methods, poses challenges for efficient resource utilization.

Beyond conventional deposits, alternative lithium sources are gaining attention (Table 1). Mine tailings and waters represent a promising resource, as evidenced by lithium concentrations of 11.8–13.7 mg/L in the Ukrainian Donbass rivers due to mining activities [22]. Similarly, bauxite mine tailings have been shown to contain Li_2O levels of approximately 0.20%, meeting industrial ore-grade thresholds [23]. In Morocco, abandoned mine tailings at Zeida and Mibladen have lithium concentrations of 60–67 mg/kg and 10–20 mg/kg, respectively, indicating potential for secondary resource recovery [24]. Lithium enrichment in coal deposits offers another untapped resource. Studies have highlighted a global trend of higher lithium concentrations in hard coals (~14 ppm) compared to low-rank coals (~10 ppm) [25]. Notably, the Pavlovsk coalfield in Russia boasts an average lithium content of 105 ppm, over ten times the global average, presenting significant extraction potential [26]. China's coalfields are particularly promising, with deposits such as Guanbanwusu (175 ppm), Antaibao (172 ppm), and Laoyaogou (163 ppm) exhibiting lithium concentrations far exceeding global averages [27]. Meanwhile, analysis of over 7500 samples from the Appalachian Basin in the USA revealed an average lithium concentration of 17.3 ppm, suggesting viability for recovery efforts [28]. Figure 4 illustrates the variation in lithium concentrations across coalfields worldwide. While LIBs remain the most efficient energy storage media, alternatives such as hydrogen fuel cells, redox flow batteries, and solar-based systems are being explored. However, these often depend on lithium or compromise performance when relying on substitutes like calcium, magnesium, mercury, or zinc. Hence, the development of sustainable lithium alternatives and recycling strategies is imperative to meet the growing demand while minimizing environmental impact.

Table 1. Summary of some mine tailing sources worldwide for their lithium contents.

Source	Lithium Concentration	Reference
Ukrainian Donbass rivers	11.8–13.7 mg/L	[22]
Bauxite mine tailings	~0.20% Li_2O (2000 ppm Li)	[23]
Zeida tailings (Morocco)	60–67 mg/kg	[24]
Mibladen tailings (Morocco)	10–20 mg/kg	[24]
Coal fly ash (USA)	50–100 mg/kg	[28]
Lithium-rich geothermal brines	400–1000 mg/L	[29]

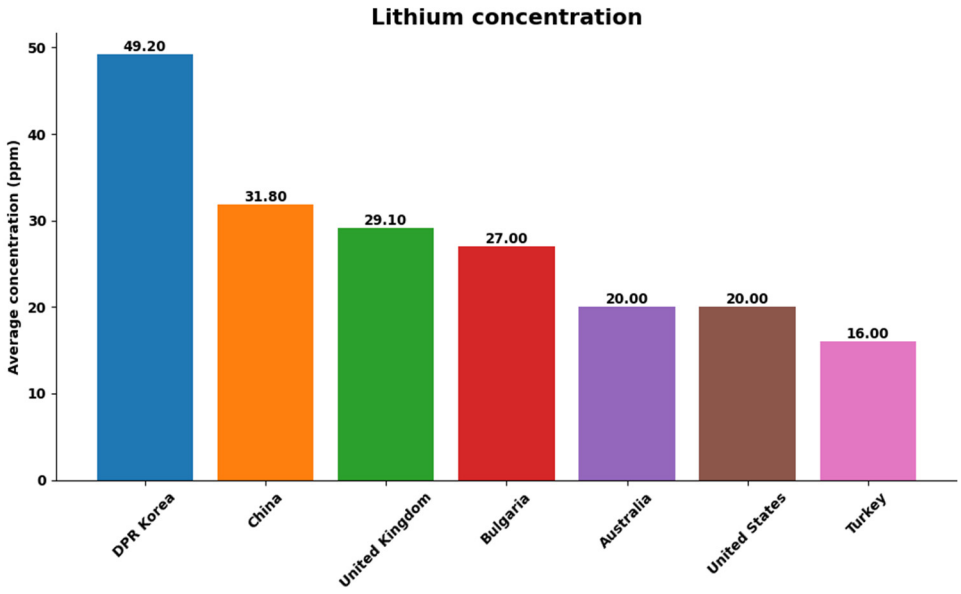


Figure 4. Average lithium concentration (ppm) within coal samples across several countries [27].

2.2. Rare Earth Elements (REEs)

Rare earth elements (REEs), a group of 15 elements, are essential in a wide range of industries, including electronics, scientific research, and defense. Currently, the global production of REEs stands at 240 kilotons, with a projected annual growth rate of 5% driven by the expansion of the renewable energy and electronics sectors [30]. The countries with the largest REE reserves, in descending order, are China, Brazil, Vietnam, Russia, and India. Together, these nations hold an estimated 130 million tons of REEs, primarily sourced from carbonatites, igneous systems, clay, and placer deposits [31].

The United States currently relies on imports to meet its demand for REEs, with the only REE-producing mine located in Mountain Pass, California. Due to the critical role of REEs in modern industries, the United States has classified them as critical minerals. Elements such as europium, dysprosium, and erbium are expected to face supply shortages due to management challenges, environmental concerns, and global accessibility issues [32]. The criticality of REEs is further compounded by the lack of viable substitutes. While some metals can replace REEs in specific applications, they typically fall short in terms of physical, chemical, and conductive properties. Thus, REEs are often substituted for one another based on their similar characteristics, making their availability crucial for technological advancements. The increasing demand and limited supply of REEs highlight the urgent need to discover new sources, as economically viable deposits remain scarce [33].

The composition of REE-bearing mine tailings varies depending on the geology, target mineral, and mining history of the deposit. For example, the rare earth elements identified

in the LKAB (Sweden) mine tailings originated from two primary mineral phases: monazite and apatite. Apatite, a calcium-based phosphate mineral, contains only trace amounts of REEs compared to the REE-rich monazite [34]. The distribution of REEs in Upgraded Apatite Concentrate from LKAB mine tailings is detailed in Figure 5.

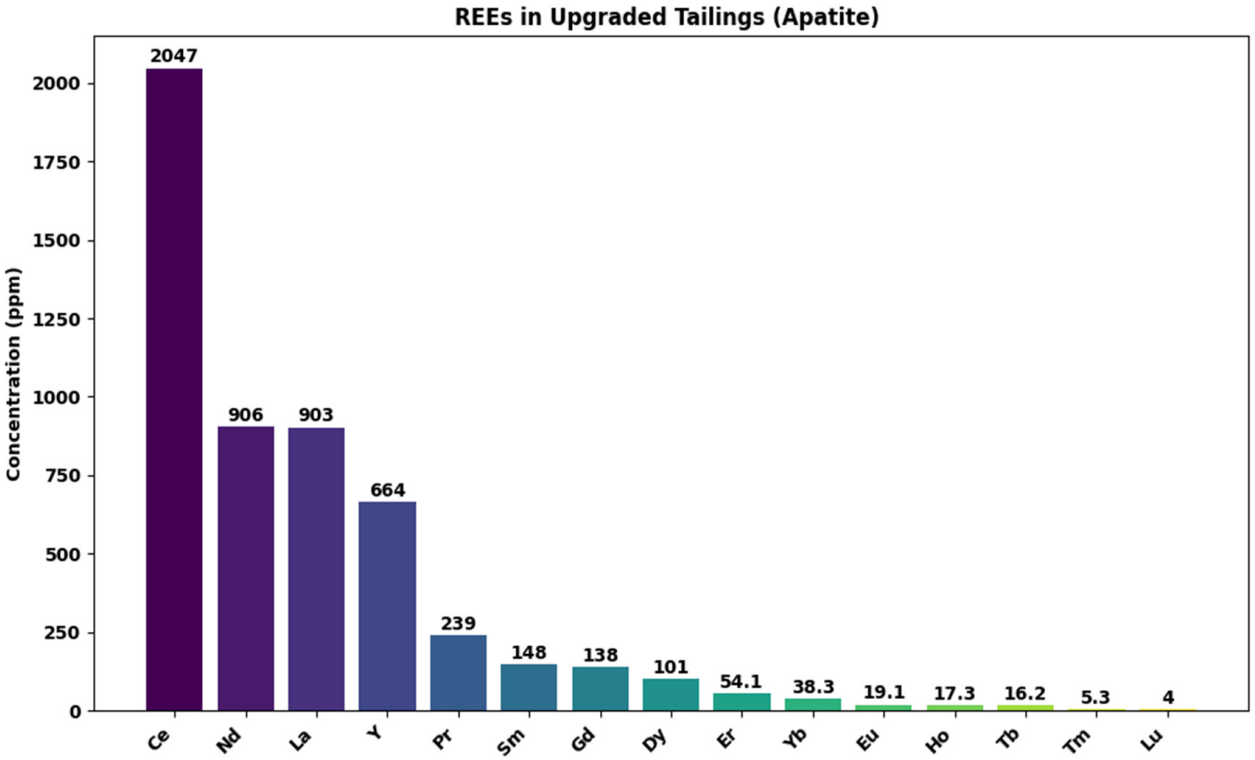


Figure 5. Distribution of rare earth elements in Upgraded Apatite Concentrate from tailings, LKAB, Sweden [35].

Beyond traditional sources, acid mine drainage (AMD) from copper, pyrite, lead, zinc, and gold mining presents a promising avenue for REE recovery. AMD is unexpectedly rich in REEs, with concentrations significantly higher than those found in natural waters, offering a compelling opportunity to enhance the sustainability of the REE supply chain [36,37]. Noack and his coworkers' study revealed that typical groundwater, lakes, and rivers contain REEs in minuscule quantities, measured in mere thousands or ten-thousandths of a microgram per liter (µg/L) [38]. Conversely, AMD showcases concentrations several orders of magnitude higher, soaring up to 17,920 µg/L as documented by Ayora et al. [39]. This dramatic disparity highlights the immense potential of AMD. The USA's Environmental Protection Agency estimates that over 5400 km of streams in the Appalachian region alone are compromised by coal mine drainage. However, this environmental challenge presents a potential silver lining: AMD could be a significant source for rare earth element recovery [36]. Table 2 emphasizes typical REEs concentrations in some of the mine drainage samples around the world compiled from recent studies.

Table 2. Typical concentrations of REEs found in some of the mine drainage samples around the world. (Modified from [34,35,37]).

Location	Type of Mine	REE Content	Key REEs Identified
LKAB Mine Tailings	Apatite, Monazite	~100–1000 ppm	Lanthanum, Cerium, Neodymium
Poland—Podwisniowka	Quartz Quarry	28,840 µg/L	Yttrium, Lanthanum, Cerium

Table 2. *Cont.*

Location	Type of Mine	REE Content	Key REEs Identified
Germany—Ronneburg Mine Site	Uranium Mine	4742 µg/L	Cerium, Dysprosium
Romania—Hanes	Cu, Zn, Pb, Ag Mine	1582 µg/L	Neodymium, Lanthanum
Brazil—Osamu Utsumi Mine	Uranium Mine	130,000 µg/L	Yttrium, Europium
Spain (IPB)—Almagrera	Zn, Pb, Cu Mine	3500 µg/L	Cerium, Neodymium
Spain (IPB)—Poderosa Mine	Pyrite, Cu Mine	9700 µg/L	Dysprosium, Neodymium
USA (Montana)—Berkeley Mine	Polymetallic, Cu Mine	2688–2914 µg/L	Cerium, Lanthanum
USA (West Kentucky)	Coal Mine	6140 µg/L	Neodymium, Lanthanum
USA (Illinois)	Coal Mine	85–9879 µg/L	Yttrium, Neodymium
USA (West Virginia, Pennsylvania)	Coal Mine	8–1139 µg/L	Cerium, Dysprosium
India—Jaintia Hills	Coalfield	169–2563 µg/L	Lanthanum, Neodymium

Coal shows promise as a source of critical and heavy rare earth elements, potentially exceeding traditional deposits. Estimates suggest a minimum concentration of 115–130 ppm for viable extraction, though the USA's Department of Energy has a more conservative threshold of 300 ppm [40,41]. Rare earth elements reside in several key mineral phases, including bastnasite, monazite, xenotime, and loparite/britholite. These minerals occur in igneous rocks, pegmatites, and placer deposits. The analysis of the rare earth element correlation with ash yield suggests a primary association with inorganic components in the coal. Globally, researchers have identified several coal deposits enriched in rare earth elements, exceeding traditional sources. These deposits, located in the Russian Far East, China, and the United States, boast concentrations ranging from 1000 to 6000 ppm [40]. In a large-scale investigation, researchers analyzed over 8000 coal samples (including rocks) from diverse regions. They found an average scandium content of 4.3 ppm in these coals, with some Siberian samples reaching a remarkable 230 ppm [26]. Notably, coal deposits in the Russian Far East (300–1000 ppm) and the Sydney Basin of Nova Scotia, Canada (72–483 ppm) have been documented to contain significantly higher rare earth element concentrations compared to the global average [41].

Coal combustion generates significant byproducts, primarily fly ash (70–85%) and bottom ash (15–30%), amounting to 45.7 million tons of coal ash annually in the United States alone. While approximately 60% of this ash is beneficially reused, the remaining portion is discarded. Research by Taggart et al. suggests that this discarded fly ash holds considerable potential for rare earth element recovery. Estimates indicate that unused fly ash from specific basins, such as the Appalachian (4000 tons/year), Illinois (1280 tons/year), and Powder River (3630 tons/year) basins, could significantly contribute to the domestic supply of REEs [42]. REE concentrations in coal ash vary widely, depending on the source of the coal. Yttrium (Y) has a global mean concentration of 58.5 ppm, with China, the USA, and Europe contributing 57.4, 68.2, and 33.1 ppm, respectively. Lanthanum (La) averages 73.1 ppm worldwide, with China at 84.4 ppm, the USA at 73.1 ppm, and Europe at 45 ppm. Cerium (Ce) has a worldwide average of 156.8 ppm, with China, the USA, and Europe contributing 176, 161.6, and 98.7 ppm, respectively. Praseodymium (Pr) averages 17 ppm globally, with China, the USA, and Europe having 19.1, 17.2, and 11.2 ppm, respectively. The worldwide average for neodymium (Nd) is 71.2 ppm, with China at 75.3 ppm and Europe at 56.2 ppm. Samarium (Sm) averages 13.2 ppm worldwide, with China, the USA, and Europe at 13.7, 14.3, and 8.6 ppm, respectively. Europium (Eu) averages 2.6 ppm worldwide, with China, the USA, and Europe at 2.5, 3, and 1.9 ppm. Gadolinium (Gd) averages 13.5 ppm worldwide, with China, the USA, and Europe at 14.1, 13.8, and 9.3 ppm.

The worldwide average for terbium (Tb) is 2 ppm, with China, the USA, and Europe at 2, 2.3, and 1.6 ppm. Dysprosium (Dy) averages 11 ppm worldwide, with China, the USA, and Europe at 11.3, 12.3, and 7 ppm. The USA and China have 2.2 ppm of holmium (Ho) whereas Europe has 1.2 ppm. Erbium (Er) averages 6.9 ppm globally, with the USA, China, and Europe at 7.7, 6.5, and 4.4 ppm, respectively. Europe has 0.5 ppm thulium (Tm), the USA 1 ppm, and China 0.9 ppm. Globally, Ytterbium (Yb) averages 5.8 ppm, with China, the USA, and Europe at 5.9, 6.5, and 3.9 ppm. Lutetium (Lu)'s worldwide average is 0.8 ppm, with China, the USA, and Europe at 0.9, 0.9, and 0.6 ppm [27,40,43]. Interestingly, the USA's coal ash samples have shown higher concentrations of REEs compared to other regions, with some samples exceeding 525 ppm, particularly in West Virginia [44]. Figure 6 shows the average concentration of rare earth elements in coal-based resources in the United States, including in situ, coal refuse, coal combustion residue, and acid mine drainage. The USA's coal resources exhibit significant variability in rare earth element concentrations. In situ deposits contain an average of 119.79 ppm REEs, encompassing all lanthanides and scandium. Coal combustion residuals (CCRs) and acid mine drainage show enriched REE contents, reaching 599.90 ppm and 498.01 µg/L, respectively. Figure 7 provides a detailed breakdown of individual REE concentrations (ppm) across various types of coal.

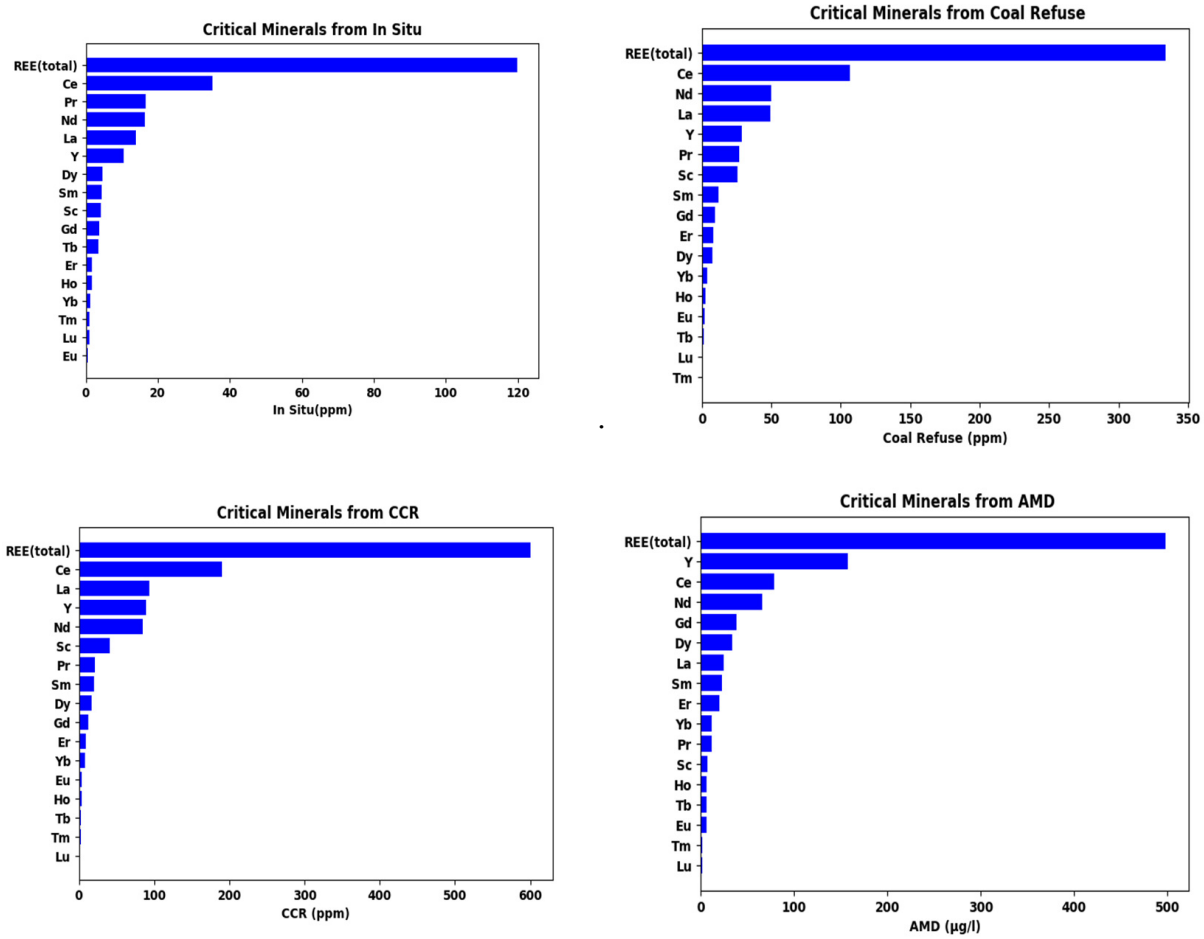


Figure 6. The mean concentration of rare earth elements in coal-based resources within the USA [27,45].

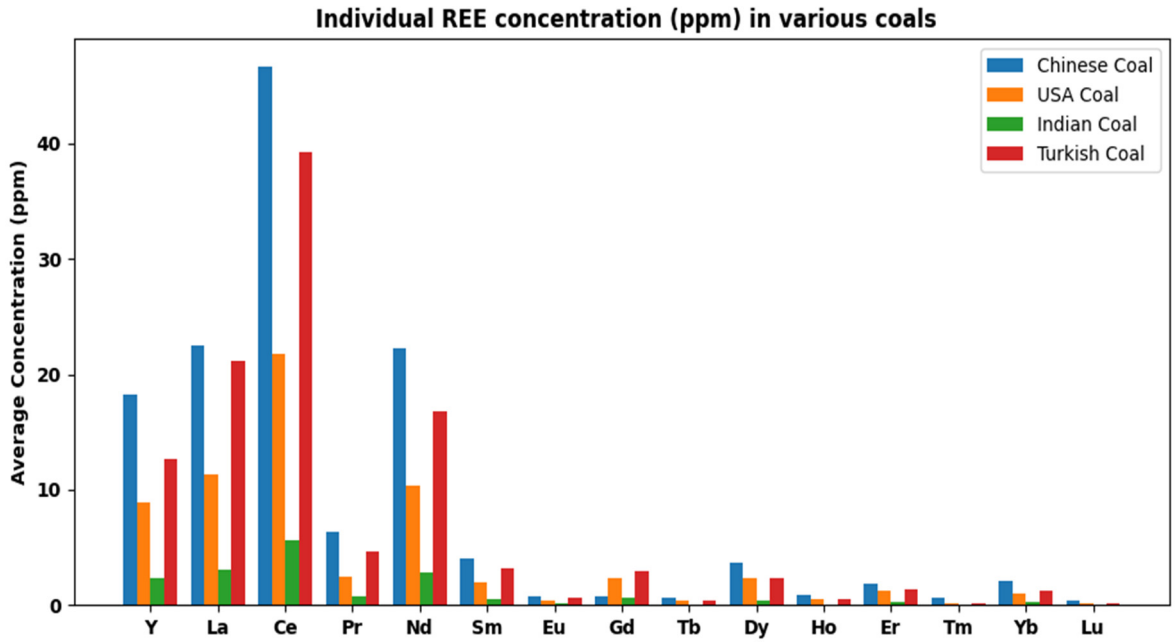


Figure 7. Individual rare earth element concentration (ppm) in various coals [27,40,46–49].

It is important to note that the graphs do not include promethium (Pm) due to its radioactive nature and scarcity in both traditional and secondary (coal-based) sources. However, other radioactive elements such as thorium and uranium are frequently observed in rare earth element (REE) mineralization, regardless of the source. This occurrence is primarily attributed to isomorphic substitution or, in some cases, epigenetic infiltration during the lignite to subbituminous stage of coalification, as noted by Talan and Huang [50]. The presence of radioactive elements is often associated with monazite mineralization, which can take forms such as (Ce, La, Nd, Th)PO_4, (La, Ce, Nd, Th)PO_4, or (Nd, Ce, La, Th)PO_4 and may contain up to 20 wt% ThO_2 and 16 wt% UO_2 [50]. Other forms of REE mineralization, including bastnäsite and xenotime in coal-based sources, may also contain radioactive elements, though typically in lower concentrations.

2.3. Cobalt

Cobalt is increasingly recognized as a critical mineral, essential to various emerging technologies, particularly in the fields of energy storage, aerospace, and high-temperature applications. Cobalt is a key component in lithium-ion rechargeable batteries, superalloys, and cemented alloys due to its robust properties such as high wear resistance and high-temperature stability [51–53]. These attributes make cobalt indispensable in the aerospace sector, where it is used in jet engines, turbines, and other high-performance components. In recent years, cobalt's strategic importance has surged with the rapid growth of electric vehicles (EVs) and renewable energy storage systems, which rely on lithium-ion batteries that contain cobalt as a crucial element. According to a forecast by Alves Dias et al., the number of electric vehicles globally is expected to reach 130 million by 2030, a 40% increase from 2017 levels [54]. Furthermore, Fu et al. predict a dramatic rise in demand for lithium batteries, which will increase the demand for cobalt by an estimated 235 to 430 kilotons by 2030 [55].

Cobalt is rarely found in isolation and is usually present alongside other metal-bearing minerals. In the context of mine tailings, cobalt is often found in the mineral assemblages of sulfides like chalcopyrite ($CuFeS_2$), pyrite (FeS_2), and cobaltite (CoAsS), as well as in other minerals like linnaeite (Co_3S_4). These minerals can have varying concentrations of cobalt, depending on the specific geological and mineralogical conditions of the ore deposit.

For instance, in minerals such as pyrite, the concentration of cobalt is relatively low but still significant. The chemical composition of strategic cobalt in selected mineral groups is shown in Figure 8, illustrating the distribution of major elements in these minerals. For example, the mean concentrations of Fe, S, Cu, and Co in Carrollite, and chalcopyrite are 27.79%, 33.06%, 18.82%, and 1.06% by weight, respectively. Pyrite, specifically, has an elemental composition of 38.30% iron (Fe), 0.30% sulfur (S), 0.20% copper (Cu), 0.02% zinc (Zn), and 1.38% cobalt (Co).

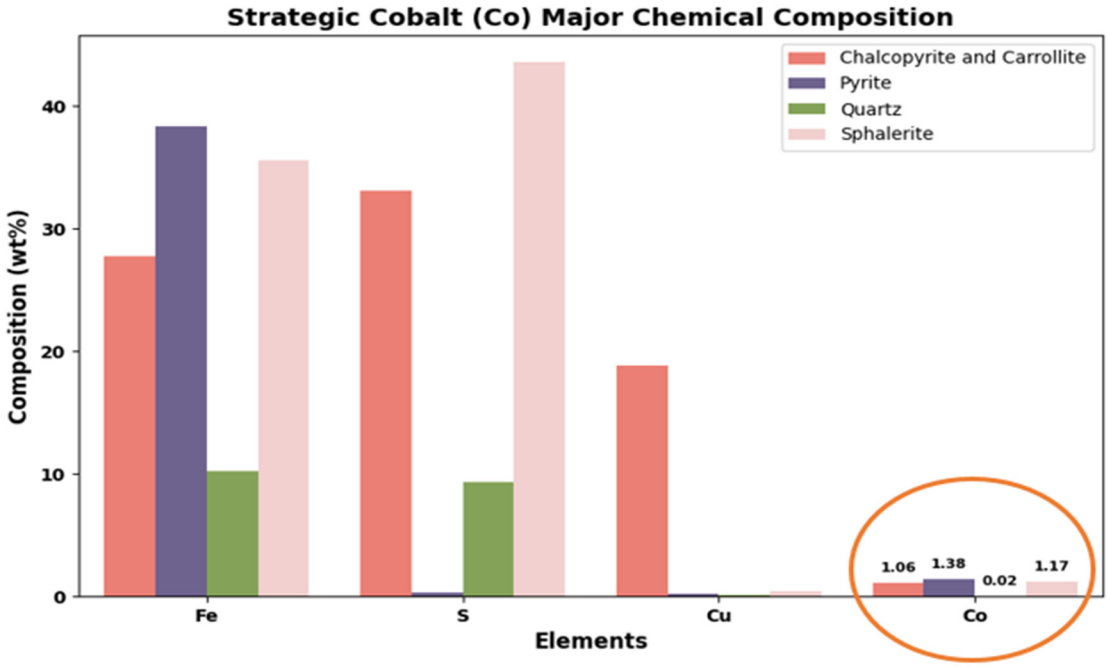


Figure 8. Strategic cobalt (Co) major chemical composition in selected mineral groups [56–59].

Cobalt is not typically found in large quantities in coal-based resources, but it can be present in trace amounts in certain coal deposits. The extraction and availability of cobalt from coal resources are largely constrained by the concentration of cobalt-bearing minerals in these deposits. Ketris and Yudovich found that low-rank coals generally contain cobalt concentrations of around 4.2 ppm while hard coals typically have a slightly higher concentration of 6 ppm. Interestingly, coal samples from China and the USA were found to have cobalt concentrations significantly higher than those from Australia. For instance, the United States had a higher average cobalt concentration of 6.1 ppm, with some samples showing concentrations as high as 500 ppm [28,60]. Recent studies have also shown that certain coalfields, such as those in Nigeria's Lower and Middle Beneu Troughs, exhibit cobalt concentrations above the global average. For example, the Lower Beneu Trough contains the highest concentration of cobalt among these areas. In contrast, the Pavlovsk coalfield in Russia was found to have a mean cobalt concentration of 10 ppm, which is notable for its higher germanium content [61]. These findings suggest that certain coal deposits may offer untapped cobalt resources, though the concentration remains relatively low compared to primary cobalt-producing mines. Table 3 below summarizes the cobalt contents found in various types of mine wastes, including tailings, slag, and acid mine drainage, from different mining operations worldwide. These concentrations vary widely, depending on the geology, mineralogy, and mining processes involved. The table provides an overview of cobalt content in different mine wastes evaluated in recent years, highlighting the potential for cobalt recovery from these sources.

Table 3. Overview of cobalt content in different mine wastes.

Location	Type of Mine Waste	Cobalt Content	Key Cobalt-Bearing Minerals	Reference
Canada (Sudbury)	Copper–Nickel Tailings	25–500 ppm	Cobaltite (CoAsS), Skutterudite ($CoAs_3$)	[45]
DRC (Katanga)	Copper–Cobalt Tailings	100–1500 ppm	Cobaltite, Glaucodot ($FeCo_2S_4$)	[55]
Russia (Norilsk)	Nickel Slag	500–1000 ppm	Cobaltite, Pentlandite (Ni, Fe, Co)	[47]
Indonesia (Sulawesi)	Nickel–Copper Slag	200–600 ppm	Cobaltite, Pentlandite	[27]
USA (Arizona)	Copper Smelting Slag	150–400 ppm	Cobaltite, Cu-Co sulfides	[26]
USA (Appalachia)	Acid Mine Drainage (AMD)	10–100 µg/L	Cobalt-bearing sulfides	[37]
Chile (Atacama Desert)	Copper Mine Tailings	50–400 ppm	Cobaltite, Erythrite ($Co_3(AsO_4)_2 \cdot 8H_2O$)	[62]
Philippines (Surigao)	Nickel–Cobalt Mine Tailings	100–700 ppm	Cobaltite, Cobaltian Pyrite	[45]

2.4. Nickel

The significance of nickel has elevated asto make it a vital metal, being increasingly utilized across various sectors including engineering, transportation, architecture, building, and construction. Its notable importance is particularly highlighted in the field of clean energy [63,64]. This metal's versatility, including formability, ductility, corrosion resistance, and malleability, makes it ideal for various industrial applications. Nickel, used in the metal and mining industry, accounts for two-thirds of the world's nickel mined, primarily used in producing stainless steel and non-ferrous alloys for specialized applications (Figure 9). Batteries containing nickel enhance energy density, decrease size, and are capable of being recharged and reused [65].

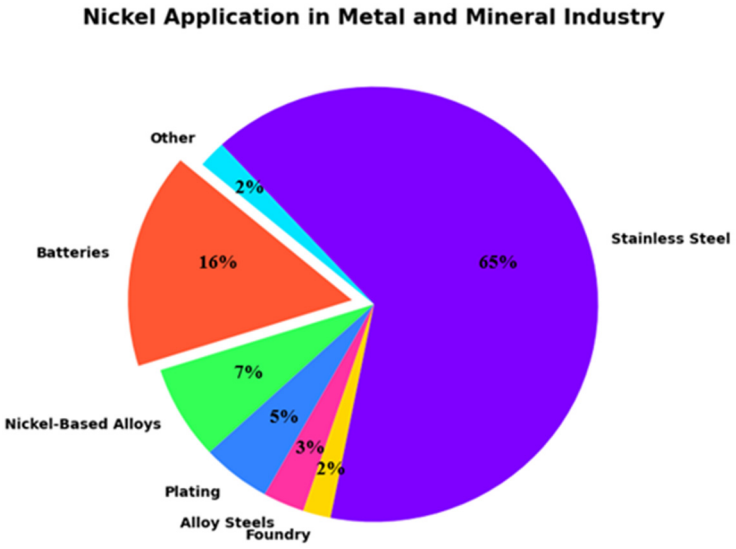


Figure 9. Nickel application in metal and mineral industry in 2023 [64].

Nickel is abundant in ferrous and non-ferrous environments. Iron-rich laterite deposits contain Ni-bearing ore minerals like limonite, smectite, and garnierite due to intensive weathering [66]. Nickel is globally abundant, with land resources estimated at approximately 300 million metric tons. About 60% of these resources are found in laterite deposits while the remaining 40% are in sulfide deposits [63]. Figure 10 illustrates the worldwide distribution of Nickel resources based on the type of deposit. Nickel production generates

substantial tailings that occupy millions of acres globally. These tailings, derived from nickel-containing sulfide and oxide ores (e.g., laterites), often contain significant quantities of Ni, Co, Fe, Mg, and Cr [67]. Processing laterite ores is more complex and costly than processing sulfide ores due to their high moisture contents, requiring extensive treatment and drying. However, advancements in mining and processing technologies have reduced these costs, making nickel extraction from laterite ores increasingly competitive [68,69]. Table 4 summarizes nickel content of various mine tailings.

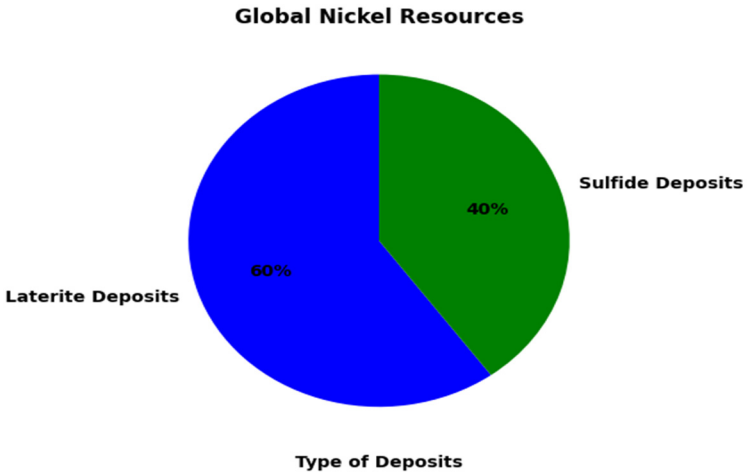


Figure 10. Global distribution of Ni resources based on deposit types in 2022 [63].

Table 4. Overview of nickel content in different mine wastes.

Location	Tailings Type	Nickel Content (wt%)	References
Sudbury, Canada	Pyrrhotite Tailings	~0.8	[70]
Moa, Cuba	Laterite Tailings	0.34	[71]
Jøssingfjorden, Norway	Sulfide Tailings	Variable	[72]
Philippines	Laterite Tailings	1.0–1.6	[73]
Sudbury, Canada	Pentlandite–Chalcopyrite	34.25 (Pentlandite)	[70]
Indonesia	Laterite Tailings	1.5	[68]

3. Recovery Strategies

The recovery of valuable minerals from tailings is an essential component of sustainable mineral processing. Tailings vary widely in their physical and chemical properties depending on the ore deposit and processing techniques used. Characteristics such as particle size, density, magnetic properties, and mineral composition significantly influence the effectiveness of physical separation methods. These methods, which use physical and mechanical principles to separate minerals from waste, are vital for improving recovery rates and enhancing resource efficiency. One of the most widely used methods for mineral separation is flotation, which exploits differences in surface properties between minerals and gangue. Flotation can be effectively used to separate valuable minerals from gangue by exploiting differences in their hydrophobic properties. Coarse particles are typically processed using fluidized bed reactors while fine particles are handled with reactor–separator-induced air reactors. The choice of reactor type and its suitability depend on the characteristics of the ore and the desired level of separation. This technology plays a vital role in recovering critical metals from mining and processing wastes [74].

For example, flotation has been successfully applied to reprocess sphalerite tailings in Sardinia, recovering valuable metals like lead and zinc while also achieving environmental

remediation [75]. Additionally, flotation has been used to recover rare earth elements from mine tailings through various advanced techniques including ion flotation, solvent sublation, electroflotation, and absorbing colloid flotation. These methods use surfactants and bubbles to concentrate and recover REEs, with each technique utilized for specific waste types [76]. However, some tailings contain minerals that are difficult to recover through physical separation due to their fine particle size and complex mineralogy. In such cases, hydrometallurgical approaches offer an alternative solution for recovering valuable elements. For instance, bioleaching has been used to extract copper and gold from low-grade sulfide tailings [77]. Additionally, acid leaching and solvent extraction have proven effective in recovering critical minerals like rare earth elements and lithium from mine tailings [78]. These chemical methods allow for selective metal recovery by dissolving the target components and separating them from impurities, often resulting in higher recovery rates. However, tailings generated from flotation typically contain fine particles and residual reagents, requiring careful management to mitigate environmental risks and optimize resource recovery.

Magnetic separation is a critical technique that uses the magnetic properties of certain minerals to achieve separation. By creating preconcentrates, this technique can improve the recovery of critical minerals, such rare earth elements, from low-grade tailings. Particularly, wet magnetic separation has shown promise in separating REE minerals from gangue materials, producing valuable preconcentrates that can be enhanced further using techniques such as froth flotation [79].

Combining magnetic roasting with diagnostic grind–magnetic separation has shown to be a promising method for enhancing the recovery of rare earth elements and upgrading tailings [79]. For instance, magnetic separation was successfully applied at a South Australian mining operation to recover and upgrade REEs from low-grade, fine-sized tailings containing iron oxide and silicate minerals. A wet high-intensity magnetic separator was used, achieving a 51% recovery of REE at a concentrate grade of 1.25%. The effectiveness of the separation process was influenced by factors such as magnetic field intensity, particle size, and the mineralogical characteristics of the tailings [79]. In addition to REE recovery, high-intensity magnetic separation combined with flotation has shown potential for improving sulfide mineral recovery and reducing arsenic content in Au-Cu tailings. Taskinen et al. demonstrated enhanced selectivity by integrating high-gradient magnetic separation and a hydro-cyclone with flotation [80]. The use of a hydro-cyclone reduced the arsenic concentration from 0.017 to 0.008%, and subsequent processing brought it down further to 0.003%. This method effectively recovered Cu, Au, and FeAsS while significantly minimizing arsenic levels in the final tailings, showcasing its effectiveness in reducing environmental risks while optimizing mineral recovery.

While magnetic separation techniques, as demonstrated by Bai et al. and Hou et al., are effective in recovering iron and rare earth elements from tailings, hydrometallurgical methods can further refine the recovery process, especially for metals in finely distributed or low-grade ores [81,82]. Hydrometallurgy, which includes processes such as acid leaching, solvent extraction, and electrowinning, offers significant advantages for extracting metals from complex ore matrices that magnetic separation cannot efficiently address. For example, acid leaching can dissolve metals from laterite nickel ores or low-intensity magnetic separation tailings, followed by solvent extraction to selectively recover valuable metals like nickel, cobalt, and rare earth elements.

Gravity separation is another widely employed method, relying on differences in density between minerals and waste material. Jigs and shaking tables are examples of traditional gravity separation technologies that are useful for reprocessing tailings [83]. The Multi-Gravity Separator, a combination of a centrifugal separator and a shaking table,

separates particles based on density. Factors such as the wash water flow, amplitude, frequency, and angle of tilt play significant roles in performance. Studies have shown that the particle size, feed grade, tilt angle, and shake amplitude can improve the recovery efficiency and grade significantly [84].

Klein et al. demonstrated that the Knelson concentrator offers a promising solution for recovering coarse Au and Ag particles lost during flotation [85]. Pilot experiments achieved recoveries of 20% for Au and 8.9% for Ag. At the plant scale, the KC effectively scavenged coarse particles, resulting in a recovery efficiency of 6.8% and an Au grade of 9.8 g/t [85]. Similarly, at Kipushi, Katwika et al. demonstrated the effectiveness of the Knelson batch concentrator in recovering Cu and Co with high talc contents [86]. Laboratory tests revealed that mineralogy and metal concentration significantly influence the recovery efficiency and grade. Under optimal conditions, the Knelson concentrator process can increase production capacity by 0.65 t/h for Cu and 0.14 t/h for Co, highlighting its potential to enhance copper and cobalt recovery from tailings [86]. While gravity separation methods like jigs, shaking tables, and centrifugal separators excel at recovering coarser particles based on density differences, they often struggle with fine particles and complex ores. However, they often struggle to process fine particles and complex ores due to insufficient residence time for microscopic particles. Consequently, these methods are less effective at filtering out fine particles [83]. Hydrometallurgy, on the other hand, uses chemical processes like leaching to selectively dissolve valuable minerals, providing higher recovery rates for fine and ultra-fine particles that gravity methods cannot efficiently treat.

While physical separation methods are highly effective in primary ore processing, secondary recovery processes have gained prominence in recent years, particularly for extracting minerals from tailings and other forms of mine waste. Techniques such as solvent extraction, leaching, and bioleaching dissolve minerals into solutions or use microorganisms to break down complex mineral structures. Secondary recovery processes often deal with lower concentrations of minerals compared to primary sources and must address the challenges posed by variable mineral composition in tailings.

3.1. Hydrometallurgical Approach

3.1.1. Leaching

Leaching is a cornerstone of hydrometallurgical extraction processes, particularly for recovering critical minerals from mine tailings. This process involves dissolving valuable minerals from solid materials into a liquid solvent, which is typically an acidic or alkaline solution. The subsequent recovery of the minerals is achieved through additional steps such as precipitation, solvent extraction, ion exchange, and adsorption. Leaching is especially advantageous for processing tailings as it can handle low-grade and complex mineral compositions economically and sustainably. The versatility of leaching methods has made them a key tool in addressing the rising demand for critical minerals such as REEs, lithium, cobalt, and nickel.

One of the most widely used leaching methods is acid leaching, which employs strong acids like sulfuric acid, hydrochloric acid, or nitric acid to dissolve minerals from mine tailings. This technique is particularly effective for extracting metals like REEs, lithium, and transition metals. For example, sulfuric acid leaching has been extensively applied to extract lithium from spodumene-bearing tailings as sulfuric acid is effective in breaking down lithium-bearing minerals and converting them into soluble forms. Acid leaching is also commonly used for extracting REEs from phosphogypsum and monazite-bearing tailings, utilizing its ability to dissolve REE oxides efficiently. The relative simplicity and effectiveness of acid leaching make it one of the go-to methods for many mining operations, especially when dealing with ores and tailings that contain significant quantities

of valuable minerals. Nickeliferous pyrrhotite, which contains valuable metals like nickel (Ni), copper (Cu), zinc (Zn), and cobalt (Co), can be recovered from mining tailings through pyrometallurgical processes. These methods involve oxidizing iron and sulfating nickel and copper to enable hydrometallurgical leaching [70,87]. Limonitic laterites, despite their low nickel contents (1–1.6%) and high iron concentrations, require significant sulfuric acid input for effective nickel leaching during hydrometallurgical processing [73]. For instance, Zhuang et al. demonstrated that 2% sulfuric acid could extract 13.5 kg of nickel per ton from limonitic laterite waste tailings, achieving 70% purity [88]. To mitigate the high costs of leaching methods, some studies have explored chelating agents and cation exchange resins to adsorb nickel from leachate efficiently. While acid leaching is widely used, alkaline leaching offers an alternative for minerals that are resistant to acid attack. This method utilizes reagents such as sodium hydroxide or sodium carbonate to selectively dissolve minerals like uranium, aluminum, and certain critical metals. For instance, alkaline leaching has been employed to recover scandium from bauxite residue, also known as red mud. Scandium is a rare earth element often found in low concentrations in bauxite tailings, and alkaline leaching provides a selective and efficient method for extracting it. Researchers have demonstrated that alkaline leaching could dissolve scandium compounds from red mud without affecting other elements, which is a significant advantage for recovering valuable metals from complex tailings. While alkaline leaching is not as widely used as acid leaching, its selectivity and ability to process more challenging ores make it a promising alternative for certain applications.

Chloride leaching, which involves the use of chloride-based solutions, has gained significant attention in recent years as a method for extracting critical minerals, particularly REEs, from refractory ores and tailings. Chloride leaching offers several advantages, including its ability to dissolve minerals that are difficult to process with traditional acid or alkaline methods. This makes chloride leaching particularly effective for processing tailings with complex mineral matrices or minerals that are less soluble in conventional leaching solutions. Recent studies have shown that chloride leaching can provide high extraction efficiency for REEs, and its compatibility with downstream recovery techniques like solvent extraction makes it a promising tool for addressing the growing demand for rare earth elements. Ammoniacal leaching, which uses ammonium-based solutions, has proven to be an effective method for extracting nickel and cobalt from lateritic ores and their corresponding tailings. This method is particularly advantageous for the selective recovery of nickel and cobalt, two critical metals with increasing demand in industries like electric vehicle manufacturing. Ammoniacal leaching allows for high recovery rates of nickel and cobalt while leaving other metals largely unaffected. Its compatibility with downstream recovery techniques, such as solvent extraction, further enhances its efficiency and makes it a valuable option for recovering nickel and cobalt from complex mine tailings. Researchers have shown that ammoniacal leaching can be fine-tuned to optimize the extraction of specific metals, offering an efficient and selective approach to recovering valuable critical minerals.

Emerging leaching techniques, including electrochemical and redox-potential-dependent chalcopyrite leaching, show significant promise for improving recovery rates and reducing environmental impacts. For instance, Phuong Thao et al. explored electrochemical methods for enhancing lithium recovery from chalcopyrite-containing tailings, demonstrating that these techniques could offer a more energy-efficient alternative to traditional acid leaching [89]. Additionally, mixed acid leaching techniques have been investigated for lithium recovery from bauxite mine tailings. Researchers have found that lithium can be efficiently extracted from tailings with low Li_2O content using mixed acid leaching, indicating that bauxite mine tailings could become valuable sources of lithium.

These emerging methods hold great potential for increasing the efficiency of critical mineral extraction while minimizing environmental concerns.

3.1.2. Precipitation

Once leachate is generated, additional steps such as precipitation play a crucial role in purifying and recovering valuable metals. Precipitation involves the conversion of dissolved metal ions into solid compounds, which can be separated from the solution by adjusting parameters such as the pH, temperature, and reagent concentration. This step is vital in isolating and concentrating metals, making them available for further processing. The efficiency of precipitation is influenced by several factors, including the chemical properties of the metal ions, the composition of the leachate, and the reagents used in the process.

The fundamental principle of precipitation is the exceeding of the solubility limit of a metal compound in a solution, either due to chemical reactions or physical changes in the solution environment. This process results in the formation of insoluble compounds such as salts, hydroxides, sulfides, or oxalates. These precipitates can then be removed from the liquid phase through filtration, washing, and further processing steps to recover the target minerals in a usable form. Precipitation methods can be highly selective, allowing for the efficient recovery of specific metals even in complex solutions containing multiple dissolved elements. As a result, precipitation plays a key role in improving the recovery and purity of critical minerals such as cobalt, REEs, nickel, and lithium from mine tailings.

One of the most widely used precipitation methods is hydroxide precipitation. This method involves the addition of an alkaline reagent—such as sodium hydroxide, lime (calcium hydroxide), or ammonia—to increase the pH of the solution. When the pH rises, metal hydroxides such as nickel hydroxide, cobalt hydroxide, and REE hydroxides precipitate from the solution. Hydroxide precipitation is particularly effective for extracting REEs from acidic leach solutions as most REE hydroxides have low solubility at moderately high pH levels. For instance, recent studies have demonstrated the use of hydroxide precipitation for rare earth element recovery from phosphogypsum and other industrial wastes. This technique is not only effective but also widely applicable as it can be adapted to a variety of leachate compositions. Additionally, the method's simplicity and cost-effectiveness make it an attractive option for many mining operations.

Sulfide precipitation is another widely used technique, particularly for recovering base metals such as copper, nickel, cobalt, and zinc. In this process, sulfide reagents like hydrogen sulfide (H_2S), sodium sulfide (Na_2S), or ammonium sulfide ($(NH_4)_2S$) are introduced to the leach solution. The metal ions react with sulfide ions to form insoluble metal sulfides, which can then be separated from the solution. Sulfide precipitation is especially useful in the recovery of metals from low-grade ores and tailings, often in conjunction with bioleaching processes, which enhance the metal extraction by biologically generated reagents. The sulfide precipitation process is highly selective for metals such as copper, nickel, and cobalt, making it a preferred method in the recovery of these critical minerals from complex leach solutions. Another valuable precipitation technique is carbonate precipitation, which utilizes reagents such as sodium carbonate or ammonium carbonate to precipitate metals as insoluble carbonates. This method is particularly effective for extracting lithium and certain REEs. Lithium carbonate (Li_2CO_3) is commonly produced during lithium recovery from brines and leach solutions. Meshram et al. highlighted the use of sodium carbonate to selectively recover lithium from leach solutions, demonstrating the industrial applicability of this technique [90]. The selectivity of carbonate precipitation makes it a powerful tool for recovering lithium, an essential component in battery technologies.

Oxalate precipitation is also widely employed for the recovery of REEs from mine tailings and leach solutions. By introducing oxalic acid or oxalate salts to the leach solution, REEs form insoluble rare earth oxalates, which can then be filtered and calcined to produce rare earth oxides. Oxalate precipitation is particularly selective as most other metals do not precipitate as oxalates under the same conditions. This high selectivity makes oxalate precipitation an ideal method for recovering REEs from complex leach solutions. Research by Zhang and Honaker has demonstrated the recovery of critical minerals, including REEs, through oxalate precipitation and subsequent purification steps including selective re-dissolution and separation techniques (Figure 11) [91].

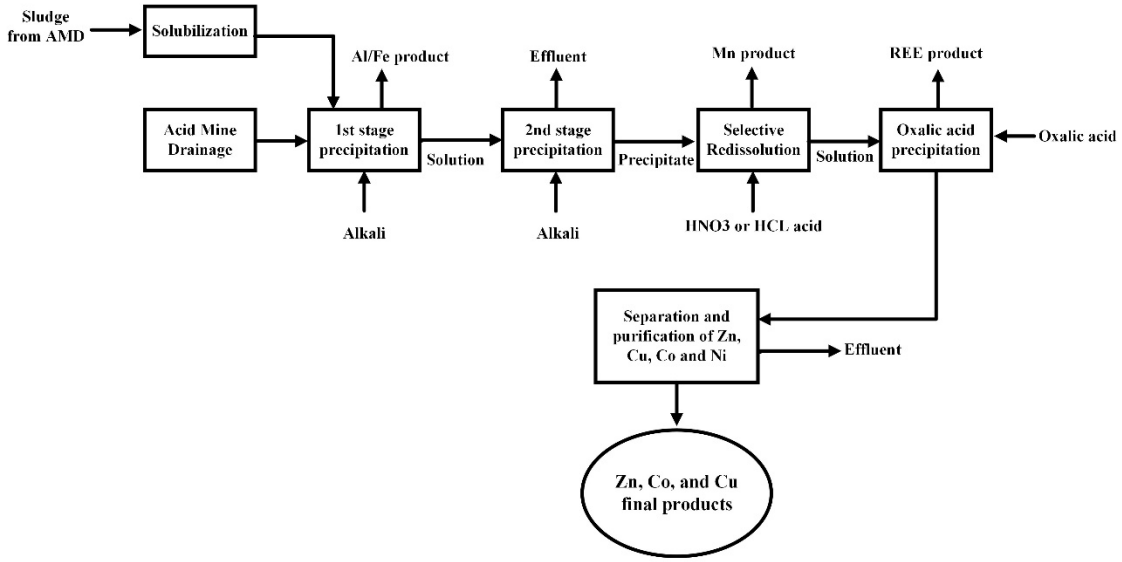


Figure 11. Rare earth elements and critical-mineral recovery flowsheet from acid mine drainage sludge [27,91].

3.1.3. Solvent Extraction

Solvent extraction is based on the principles of liquid–liquid extraction, where metal ions in the aqueous phase react with an organic extractant to form a metal–extractant complex. The organic phase, being immiscible with water, allows the metal to be separated from impurities remaining in the aqueous phase. It creates organometallic complexes through reaction with extracting reagents [92]. After extraction, the metal is stripped back into an aqueous solution using an appropriate reagent (e.g., an acid or base) and the organic extractant is regenerated for reuse. This method is particularly effective for separating metals with similar chemical properties, making it invaluable for recovering critical minerals such as cobalt, nickel, lithium, REEs, and uranium.

Solvent extraction is the primary method for separating and purifying individual REEs, which present a particular challenge due to their closely related chemical characteristics. The efficient separation of REEs from mixed solutions typically requires the use of highly selective extractants. Some of the most common extractants for REE separation include tributyl phosphate (TBP), di(2-ethylhexyl) phosphoric acid (D2EHPA), and mono(2-ethylhexyl) 2-ethylhexyl phosphonic acid (P507), which are known for their ability to selectively bind to specific REEs [93]. These extractants, often used in combination, allow for the differentiation of rare earth elements based on their varying affinities for the organic phase under different pH conditions. In the recovery of heavy rare earth elements (HREEs) from leach solutions, solvent extraction has also shown promising results. Battsengel et al. explored the extraction of HREEs from pregnant leach solutions using a variety of extractants in a sulfuric acid environment, resulting in the formation of rare earth oxalates [94]. This

method involves the use of sulfuric acid for leaching, followed by solvent extraction and precipitation to recover the target REEs. The recovery flowsheet depicted in Figure 12 illustrates this process, beginning with leaching using hydrochloric acid, followed by solvent extraction, selective precipitation, and filtration to separate and purify the rare earth elements. In this flowsheet, the solvent extraction process is essential for removing contaminants such as calcium, iron, and aluminum, which are separated during the scrubbing stage. The stripped solution is then subjected to precipitation, where the REEs are recovered as oxalates, which can be further processed to produce rare earth oxides.

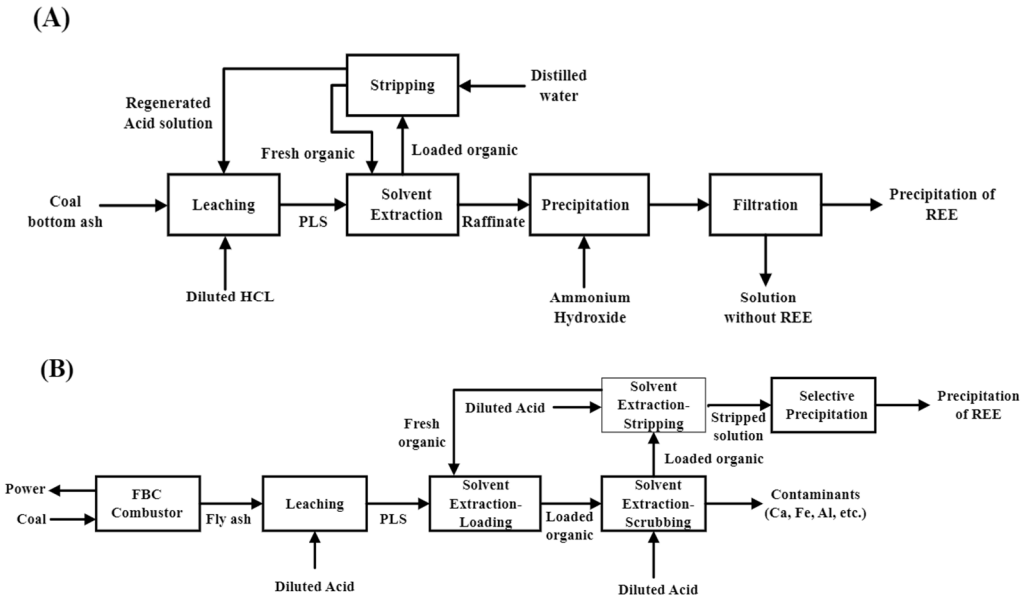


Figure 12. (**A**) Flowsheet representing recovering rare earth elements from coal bottom ash and (**B**) Flowsheet representing recovering rare earth elements from coal fly ash [27,95–97].

In addition to recovering REEs, solvent extraction is a key technique for recovering cobalt and nickel, two metals critical for battery technologies. These metals are commonly found in lateritic and sulfide ores, which are often subjected to acidic leach solutions. Extractants such as Cyanex 272 and D2EHPA are commonly employed to separate cobalt from nickel as they exhibit different affinities for these metals under specific pH conditions. Panda et al. demonstrated the effectiveness of solvent extraction for recovering cobalt and nickel from acidic leach solutions of lateritic ores, achieving high separation efficiency. This process has also been successfully applied in large-scale operations in the Democratic Republic of the Congo, where solvent extraction is used to recover cobalt from copper–cobalt ores. The ability to selectively extract cobalt from nickel using solvent extraction methods is crucial for meeting the growing demand for these metals in battery production. Lithium recovery is another area where solvent extraction has proven highly effective. Lithium-selective extractants, such as crown ethers and synergistic mixtures of organophosphorus compounds, are commonly used to efficiently separate lithium from other elements. For example, Meshram et al. discussed the application of solvent extraction for lithium recovery from brines, emphasizing its compatibility with downstream precipitation processes that produce lithium carbonate or lithium hydroxide [90]. This ability to recover lithium through solvent extraction has significant implications for the mining industry, particularly as global demand for lithium continues to rise.

Despite its numerous advantages, solvent extraction is not without its challenges. One of the primary concerns is the generation of waste and toxic byproducts, which require careful management and disposal. High-purity solvents and temperature-controlled processes are often necessary to maintain the efficiency of the extraction, adding to the

overall cost of the operation. Additionally, the use of toxic reagents such as sulfuric acid and the potential for the formation of emulsions can complicate the extraction process, requiring the meticulous control of operational conditions [98]. Furthermore, the selective extraction of specific metals from complex leach solutions often requires the use of multiple stages, including scrubbing and stripping, to achieve the desired purity and separation. This adds to the operational complexity and cost of the process.

3.1.4. Ion Exchange, Adsorption, and Membrane Processes

The application of ion exchange, adsorption, and membrane processes complements traditional methods like solvent extraction, which remains a staple in mineral recovery but is now often combined with newer, more specialized approaches to improve efficiency and sustainability [99].

Ion exchange has emerged as a highly effective method for recovering and purifying critical minerals. This process relies on ion-exchange resins, which contain functional groups capable of selectively binding metal ions. Polymeric resins, in particular, are extensively used due to their affordability, stability, and recyclability. These resins are tailored with diverse functional groups to target specific ions, offering high flexibility in application. In the recovery of REEs, strong acid-type resins, such as those based on polystyrene sulfonic acid, have proven particularly effective. These resins exhibit strong ionization capabilities, making them suitable for extracting REEs from acidic solutions, which are commonly encountered in the leaching of ores or industrial waste [100]. For example, the recovery of REEs from coal ash has been significantly improved through the use of ethylenediaminetetraacetic acid (EDTA)-functionalized resins. EDTA enhances the selective elution of REEs, allowing for higher recovery rates by facilitating the separation of rare earth elements from competing ions [101]. Similarly, weak acid resins, while offering lower ionization levels, improve the separation of REEs by reducing the co-extraction of impurities.

Ion exchange is also critical in the recovery of cobalt and nickel, which are vital for battery technologies. In the case of nickel, resins such as D201 have been used effectively to recover high-purity nickel sulfate from leach solutions of lateritic ores. This approach is crucial for meeting the growing demand for nickel in electric vehicle (EV) batteries [102]. However, ion exchange faces challenges in solutions with competing ions, which can block resin sites and reduce efficiency [103]. To address these challenges, advancements in resin technology, such as the development of solvating extractant-impregnated resins, have been employed. These resins improve selectivity by reducing the co-extraction and other impurities in complex solutions [104].

Adsorption has gained significant traction as a straightforward, cost-effective, and efficient method for recovering REEs. The simplicity of adsorption makes it particularly attractive for processing REE-rich mine tailings and wastewater. For example, in dilute solutions where conventional solvent extraction methods struggle to achieve efficiency, adsorption offers a viable alternative with lower energy and operational costs [105]. This method involves the use of adsorbents, such as activated carbon, functionalized silica, and zirconium phosphate platelets, to bind metal ions. For example, functionalized silica materials have shown great promise in selectively adsorbing REEs while avoiding co-extraction of impurities like iron [106]. Solvent-impregnated resins, such as VP1026 and TP207, combine the benefits of adsorption and solvent extraction, offering high selectivity and efficiency in removing impurities from acidic mine wastewater and enhancing critical-mineral recovery. By controlling the pH with NaOH, these resins have achieved effective separation, demonstrating their potential for practical applications [107]. In the case of lithium recovery, adsorption methods have also shown promise. Lithium, which is

a critical component of rechargeable batteries, can be selectively adsorbed from brine solutions using functionalized adsorbents. For example, lithium-selective materials have been developed for the efficient recovery of lithium from leachates of spodumene and other lithium-bearing minerals. The use of adsorbents in such processes offers a low-cost alternative to conventional solvent extraction, particularly in scenarios where the lithium concentration in the solution is low [105].

Pressure-driven membrane filtration, with methods such as nanofiltration (NF) and reverse osmosis (RO), has emerged as a complementary technique in the recovery of critical minerals. These processes utilize semi-permeable membranes to selectively separate metal ions from leach solutions, offering advantages such as reduced energy consumption and high selectivity. Polymer inclusion membranes (PIMs) and electrodialysis membranes, in particular, have shown promise in improving the transport flow and selectivity of REEs. Factors such as feed composition, solution temperature, and current density significantly influence their performance. The integration of membrane processes with traditional hydrometallurgical techniques, such as flotation and solvent extraction, can further enhance efficiency. For example, combining nanofiltration with flotation has been shown to reduce membrane fouling and improve the purity of REE concentrates, making it an attractive option for large-scale recovery operations [108]. Additionally, membrane processes have been used in combination with other recovery techniques to remove contaminants from leach solutions, thus improving the overall recovery rates of critical minerals such as cobalt and nickel. In addition to traditional membrane techniques, the development of new membrane materials and configurations is ongoing. For instance, electrodialysis membranes have been used to improve the transport flow and selectivity of REEs, offering enhanced efficiency in metal recovery from complex solutions [65]. Despite the significant advantages offered by ion exchange, adsorption, and membrane processes, several challenges remain in the recovery of critical minerals from complex matrices. The presence of competing ions and impurities, such as calcium and magnesium, can interfere with the efficiency of these methods, particularly in the case of REE recovery. To overcome these challenges, ongoing research is focused on developing more selective materials and optimizing process conditions. A summary of hydrometallurgical processes is given in Table 5.

Table 5. Summary of hydrometallurgical processes.

Method	Advantages	Challenges
Acid Leaching	Effective for dissolving a wide range of metals; relatively simple process; well studied and widely adopted.	High acid consumption; potential environmental hazards due to acid waste; corrosion of equipment.
Alkaline Leaching	Selective dissolution of specific minerals; lower environmental impact compared to acid leaching.	Less effective for metals soluble in acidic conditions; requires precise control of reagent concentrations.
Chloride Leaching	High extraction efficiency for complex ores; compatible with downstream recovery techniques like solvent extraction.	Potential generation of toxic chlorinated byproducts; higher reagent costs.
Ammonia Leaching	High selectivity for nickel and cobalt; compatibility with solvent extraction methods.	Limited application beyond nickel and cobalt; ammonia handling and recovery challenges.

Table 5. *Cont.*

Method	Advantages	Challenges
Hydroxide precipitation	Cost-effective and simple; adaptable to various leachate compositions.	Requires precise pH control; potential co-precipitation of impurities.
Sulfide precipitation	Highly selective for specific metals; compatible with bioleaching processes.	Toxicity concerns with sulfide reagents; risk of hydrogen sulfide formation.
Carbonate Precipitation	Selective recovery of lithium; high industrial applicability.	Requires precise process control; co-precipitation risks.
Oxalate Precipitation	Highly selective for REEs; minimal interference from other elements.	Additional processing required to convert oxalates to usable oxides.
Solvent Extraction	Effective for separating metals with similar properties; reusable organic extractants.	High costs; toxic byproducts; operational complexity with multiple stages.
Ion Exchange	High flexibility and selectivity; recyclable resins.	Competition from other ions can reduce efficiency; resin fouling concerns.
Adsorption	Cost-effective and straightforward; suitable for dilute solutions.	Lower efficiency for concentrated solutions; adsorbent regeneration challenges.
Membrane Processes	High separation efficiency; minimal chemical use.	Membrane fouling; high operational costs; limited application for complex solutions.

3.2. Bio-Based Methods

Advances in biotechnology have greatly expanded bio-hydrometallurgical methods, making it possible to extract metals from lower-grade sources like coal, industrial, and mining wastes [10–111]. Table 6 summarizes these processes. Bio-hydrometallurgy is a cost-effective method for extracting minerals from low-grade sources through biowethering and bioleaching, reducing operational and energy costs. The primary distinction between bioweathering and bioleaching is that bioweathering occurs naturally whereas bioleaching is a controlled process that requires the comminution of minerals and their culture in a bioreactor [112].

Aspergillus niger is a common type of bacteria used to help break down rare earth elements. Research shows that A. niger can be found in monazite ores, causing scratches on their surfaces. The bacteria release organic acids, such as oxalic acid (46 mM) and citric acid (5 mM), which help speed up the breakdown process [113]. The cited study assessed how effective biostimulation, bioaugmentation, root exudates, and water are in improving bioweathering. The results showed that bioaugmentation using *Acidithiobacillus thiooxidans* and root exudates was the most successful approach for removing metals from the environment [114]. The type of mineral affects how fast bioweathering occurs. Rocks with a goethite crust and quartz weather faster than calamine-type rocks because goethite and smithsonite are more soluble. Adding *A. thiooxidans* and *A. ferrooxidans* can speed up the bioweathering of pyrite and biotite-like minerals, leading to a 30% increase in metal release [115]. Recent research on bioleaching for lithium recovery has produced intriguing findings. A study on extracting lithium from spodumene with fungi and yeast found that *Penicillium purpurogenum* and *Rhodotorula rubra* were the most efficient microorganisms for the process [116]. Similarly, research into bioleaching from low-grade sources using

autotrophic bacteria, fungus, and yeast found that a bacterial consortium achieved the highest lithium dissolution rate, reaching 11 mg/L over 336 days [117].

Table 6. Summary of bio-based recovery methods.

Method	Key Microorganisms/ Involved Elements	Advantages	Challenges/ Limitations
Bio-hydrometallurgy	*Aspergillus niger*, *Acidithiobacillus thiooxidans*, *Penicillium purpurogenum*	Cost-effective, reduced energy costs	Requires comminution for bioleaching
Bioprecipitation	*Paraclostridium bifermentans*, *Klebsiella pneumoniae*	Faster precipitation rates, eco-friendly	Ineffective for low metal concentrations
Biosorption	*Chlorella vulgaris*, *Spirulina*, *Bacillus*, *Saccharomyces cerevisiae*	High selectivity, reusable, resistant to metal toxicity	Contamination issues, scaling challenges
Bioflotation	*Rhodococcus opacus*, *Thiobacillus ferrooxidans*	Selective flotation, high recovery rates for malachite	Expensive purification, low metal concentration
Bioelectrochemical Systems	Luo et al.'s two-chamber MECs, graphite anode, platinum-coated cathode	Efficient recovery, potential for energy production	Scalability issues, high costs

3.2.1. Bioprecipitation

Bioprecipitation is an innovative approach in mineral recovery wherein microorganisms speed up the precipitation of metals from a solution by creating phosphates, sulfides, and carbonates through oxidative–reductive reactions. Instead of using chemicals to cause precipitation, bioprecipitation uses bacteria to speed up the process. Some bacteria can change metals like manganese and iron into minerals that can trap REEs [118–120]. Through oxidative–reductive processes, microorganisms produce phosphates, sulfides, and carbonates, which help precipitate critical minerals out of solutions.

One significant process in bioprecipitation involves phosphate precipitation. In this process, microbial enzymes like polymeric matrix phosphatase assist in binding reactive oxygen species to organic phosphate. Bioprecipitation is particularly effective in microbial communities like those formed by *Paraclostridium bifermentans* and *Klebsiella pneumoniae*, achieving a recovery rate of up to 91% of soluble metals in just 30 h of incubation [48]. Biogenic sulfides created through bioprecipitation have demonstrated faster precipitation rates than synthetic sulfides, leading to metal recovery rates between 44% and 60%. Despite these advantages, bioprecipitation is not as effective in extracting ores, especially when dealing with small quantities, which limits its use in recovering REEs [121].

3.2.2. Biosorption

Biosorption is a process in which microbial biomass absorbs pollutants from aqueous solution. This process is physico-chemical in nature, independent of metabolic activity, and may encompass various retention mechanisms. The mechanisms encompass adsorption, ion exchange, complexation, chelation, reduction, and precipitation [122]. Since 2015, academic research has been increasingly concentrating on using biomaterials such as biopolymers and biochar for REE processing through ion exchange and adsorption methods. These biomaterials have been shown to have high adsorption capacities [123]. Using bacteria for bioadsorption is becoming a promising technique for separating REEs and eliminating contaminants. However, there are still challenges in effectively removing impurities like iron, thorium, and aluminum [124]. For instance, Park et al. and Tay et al. demonstrated the potential of bioadsorption in REE recovery and have shown the potential

of using bioadsorption for recovering REEs [125,126]. However, contamination continues to be a significant challenge in this process.

Using non-living microbial biomass for biosorption has many benefits compared to traditional methods. These advantages include high selectivity even at low metal concentrations, easier operational conditions, a simple desorption process, and the ability to regenerate the biomass. Unlike living microorganisms, non-living biomass is not affected by metal toxicity and does not need additional nutrients, making it suitable for long-term use [127]. The microbial cell wall is important for biosorption, especially in Gram-positive bacteria. These bacteria have a thick peptidoglycan layer that attracts and binds metal ions, helping them absorb metals efficiently [128].

Studies have also found that moss species such as *Physcomitrella patens* have high adsorption efficiencies for REEs, especially neodymium (Nd) and europium (Eu) [129]. Although biosorption shows potential for industrial use, scaling up the process poses challenges, especially in addressing contamination problems and maintaining consistency on a large scale [130]. Figure 13 illustrates the factors governing the microbial biosorption process. Using non-living microbial biomass for biosorption offers several advantages. These include improved selectivity at low metal concentrations, operating under mild conditions, easy desorption, and the ability to be regenerated. This method is not affected by metal toxicity, requires no additional nutrients, and can be used for extended periods due to its ability to be stored [127].

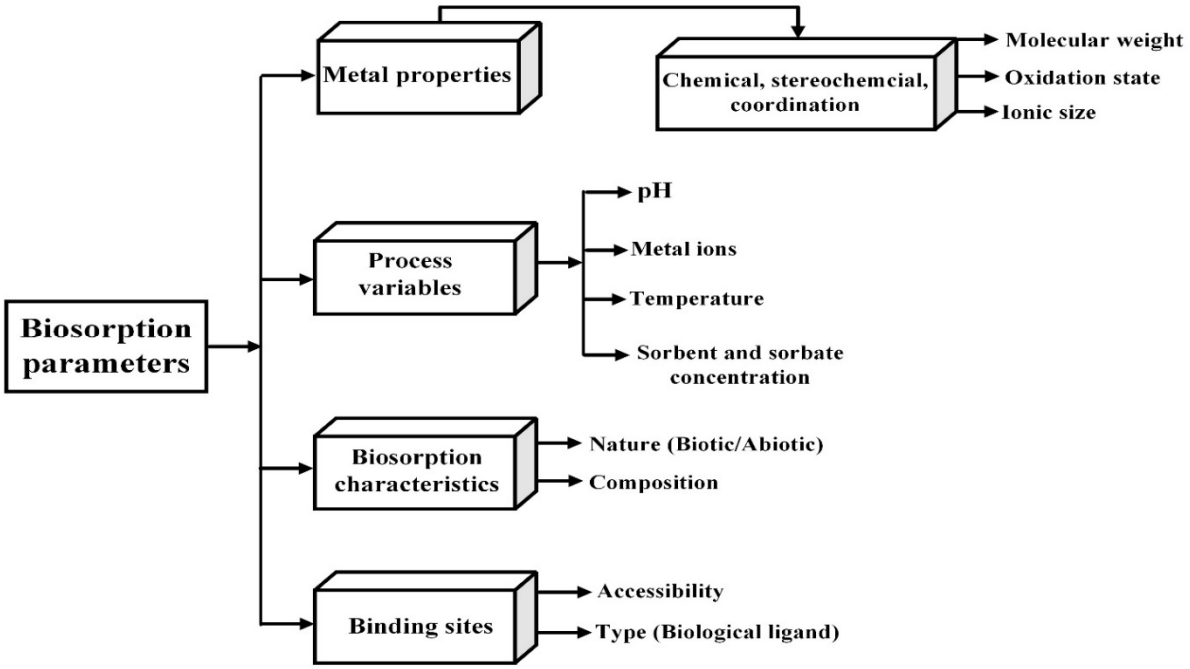


Figure 13. Factors governing microbial biosorption [131].

The bacterial cell wall plays a crucial role in determining how well bacteria can absorb metals. Gram-positive bacteria, which have a thick peptidoglycan layer, have a structural feature that helps them bind metals more effectively. The peptidoglycan layer is made up of amino acids that are connected together, creating a surface with a negative charge due to the bonds between its components. This negative charge attracts positively charged metal ions, which bacteria can then bind to and absorb from their surroundings efficiently [128,132]. Living organisms like microalgae, macroalgae, plants, and bacteria are used to adsorb REEs. Some commonly used green microalgae for this purpose are *Chlorella vulgaris*, *Calothrix brevissima*, *Chlorella kessleri*, and *Spirulina*. However, their ability to adsorb REEs varies. For

example, *C. vulgaris* can absorb neodymium at a rate of 126.1 mg/g, which is about twice as much as that of activated carbon [133].

Spirulina, a form of algae, serves as a medium for the adsorption of REEs. Commercial Spirulina powder can absorb 38.2 mg of Ce^{+3} per gram while a natural strain can only absorb 18.1 mg per gram [134]. The ability of bacteria to absorb heavy metals depends on their surface properties and how they interact with metal ions. Some types of bacteria, such as Bacillus, Enterobacter, Micrococcus, and Pseudomonas, are known to have a high capacity for retaining heavy metals due to their large specific surface areas and the presence of functional groups like teichoic acid. Pseudomonas aeruginosa was able to immobilize cobalt and nickel from a solution while Micrococcus luteus showed a strong ability to retain copper and lead [135]. Yeasts and molds are useful for recovering metals because they can generate negative charges and have unique cell wall structures. They are easy to grow and control, making them well suited for this purpose [136]. Yeasts, which are unicellular fungi, have a remarkable ability to absorb metal ions, making them effective in reducing metal pollution. Among yeast species, Saccharomyces cerevisiae has been extensively studied for its ability to absorb metal ions. Studies have shown that *S. cerevisiae* can effectively remove metal ions, making it a promising option for the remediation of contaminated water [137].

A study showed that modified E. coli bacteria can absorb more ruthenium compared to regular ion exchange resins. The modified bacteria were able to absorb 121.2 mg/g of ruthenium while the best ion exchange resin could only absorb up to 61.9 mg/g of ruthenium [138]. Extracellular polymeric substances (EPSs) are useful for removing metals from solutions. This method is cost-effective and efficient compared to traditional metal removal techniques. EPSs produced by microorganisms can bind metal ions, preventing them from being released into the environment [139]. Microorganisms produce extracellular polymeric substances that can be used for multiple sorption cycles, similar to ion exchangers. These EPSs are made up of polysaccharides, glycoproteins, and other biomolecules that can bind metal ions through ion exchange or complexation processes [140,141]. The fungal melanin found outside the cells of Armillaria cepistipes and Amorphotheca resinae can effectively retain Cu(II), Pb(II), Cd(II), and Zn(II) due to its chelating properties [142]. Pure cultures of EPSs show promise in removing metals, but their use is restricted by the need for sterility and large amounts of EPSs. EPSs can efficiently extract trace metals from a solution [139,143]. Although biosorption shows potential, current research mainly concentrates on binary or ternary metal solutions, overlooking the impact of anions. Additionally, the field primarily revolves around bacteria, which restricts the investigation of other potential microbial biosorbents.

3.2.3. Bioflotation and Bioelectrochemical System

Bioflotation is a method that uses microorganisms and their metabolic byproducts, such as surfactants and froth, to enhance the extraction of valuable minerals and metals. Microorganisms can act as selective inhibitors in this process. For example, Rhodococcus opacus has been found to attach to malachite's surface, changing its hydrophobic characteristics and greatly increasing flotation effectiveness. As a result, bioflotation applications have achieved a recovery rate of up to 93% for malachite [144]. Similarly, the microbial oxidation of pyrite and galena by organisms such as Thiobacillus ferrooxidans can help increase the recovery of REEs by changing the hydrophobic characteristics of the mineral surfaces, which in turn improves the efficiency of flotation [145]. Although bioflotation provides a new way to extract REEs, it is not as efficient as traditional methods because of the low metal concentrations and expensive purification processes.

The microbial oxidation of minerals can modify their hydrophobic properties. Organisms produce EPSs, which can bind REEs. These EPSs have foam-forming properties,

facilitating their extraction through foam collection. Alicyclobacillus species can release surfactants that help in the retrieval of REEs, with recovery rates between 80% and 90% [146]. Scaling up bioflotation faces challenges when it comes to using microorganisms. Biosurfactants might mitigate these operational constraints. However, further environmental and economic assessments are needed to determine whether pilot and commercial projects are feasible [147].

Bioelectrochemical systems are another promising bio-based approach for metal recovery. These systems use microorganisms as biocatalysts to convert soluble metals into insoluble forms, making it possible to extract them from aqueous solutions. This method allows for the extraction of metals through various mechanisms such as direct oxidation, precipitation, migration, or biological processes inside or outside microbial cells [148,149]. Bioelectrochemical systems consist of an anode, a cathode, and sometimes a separation membrane. Microorganisms create a biofilm on the anode through the oxidation of organic matter. This process involves an electrochemical reaction where metals are reduced and recovered at the cathode. The type of metal reduction (deposited, precipitated, or solubilized) at the cathode depends on the specific metal and solution properties. This method can be combined with energy production using microbial fuel cells, producing hydrogen, or creating valuable compounds in microbial electrolysis cells. Microorganisms use extracellular electron transfer to move electrons to or from solid surfaces. This can happen through soluble molecules or bacterial nanowires, making electron transfer and communication between cells easier [150].

Luo et al. used a two-chamber microbial electrolysis cell (MEC) to successfully recover copper, iron, and nickel from a solution [151]. A platinum-coated carbon substance served as the cathode while a brush made of graphite served as the anode. Iron, nickel, and copper ions were recovered in order of preference. Additionally, MECs have been successfully used to recover copper, zinc, and cadmium, with recovery efficiencies of up to 77% [152]. This technology has the potential to efficiently recover metals in a sustainable way. However, more research is required to improve its scalability and make it suitable for commercial use.

4. Environmental, Economic, and Technical Challenges

Green energy technologies heavily depend on critical minerals, but the extraction processes can lead to environmental pollution and risks to human health. This is often due to factors like mining techniques, types of ore, and local geology [153,154]. In developing nations like Ghana, India, and China, inadequate treatment methods in rare earth element recovery have led to hazardous chemical emissions, toxic metal contamination, and significant waste production [155]. Regulatory bodies and environmental agencies face challenges in establishing definitive thresholds for mineral levels in drinking water, highlighting the need to evaluate the impacts of mining and implement effective remediation programs.

In China, despite advancements in tailing reprocessing, mining operations still produce substantial amounts of dust, wastewater, and radioactive waste [156]. REE production generates byproducts like fluorine, particulate matter, acidic wastewater, and hazardous elements, including arsenic, lead, and thorium, which remain largely in the tailings and pose long-term environmental and safety risks [157–159]. While technological advancements have mitigated some environmental impacts of mineral extraction, the increasing demand for critical minerals poses a significant risk of deforestation, land degradation, and biodiversity loss [160]. Contaminated soils from heavy metal pollution present additional challenges as elevated concentrations can hinder plant growth and impact ecosystems [161]. Toxic elements from mine water bioaccumulate in aquatic species, leading to oxidative stress, potential mortality, and other adverse effects [162].

The environmental challenges associated with critical mineral extraction processes from mine tailings vary by location and require comprehensive life cycle assessments (LCA) to address these complexities. However, LCA results can be inconsistent due to system boundaries, inventory gaps, and methodological errors [163]. For example, groundwater pollution assessments in LCAs are particularly challenging due to site-specific conditions and require tailored approaches to address sulfur contamination considering different effect categories and characterization models [164]. Broadhurst et al. developed a froth flotation technique for removing sulfide sulfur from tailings [165]. While this approach increased SO_2 and CO_2 emissions, it significantly reduced the discharge of acidic solutions in the life cycle assessment. Hengen et al. evaluated active and passive AMD treatment processes at a New Zealand coal mine using LCA, finding that passive treatment had a smaller environmental footprint than active treatment [166]. In contrast, gold-containing tailings have been identified as posing the most significant environmental impact [167]. A recent LCA study conducted in China indicate that REE flotation is the second largest contributor to human toxicity, following iron flotation, despite the limited literature available on this subject [168].

Wang et al. studied the environmental effects of a recycling method that aims to extract valuable materials from rare-earth tailings at the Bayan Obo mine. The main goal is to produce a 500 ppm scandium concentrate from 3.86 million tons of tailings each year. The process involves flotation and magnetic separation to extract rare earth elements, iron, sulfur, fluorite, niobium, and scandium, promoting resource efficiency and sustainability. The TRACI 2.1 impact assessment methodology was used to quantitatively evaluate the total environmental impact of the recycling process. The LCA study evaluated the environmental impact in a quantitative way, enabling a thorough analysis and comparison of various impact categories to determine the overall environmental footprint. The result (Figure 14) suggests that the most significant environmental impact from processing rare-earth mine tailings is in the HTNC category, making up 30.27% of the overall environmental burden. Additionally, the ET and HTC categories also contribute substantially to the environmental impact, with percentages of 15.77% and 15.87%, respectively.

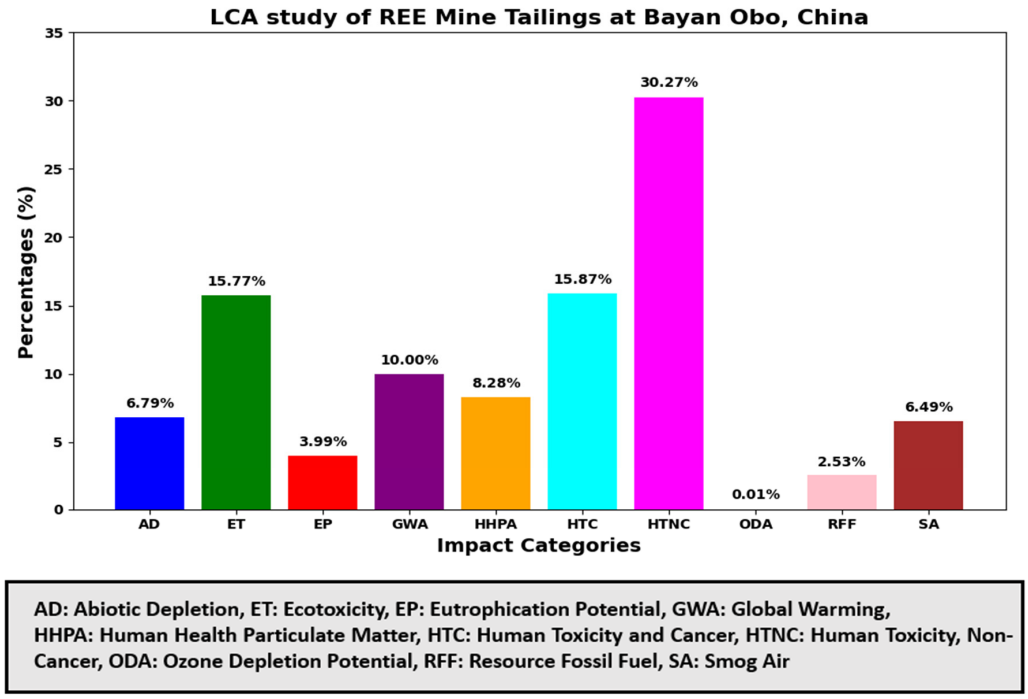


Figure 14. LCA study on rare-earth mine tailings in Bayan Obo, China: an example [168].

In evaluating cobalt and lithium extraction from mine wastes, recent studies found that cobalt sulfate extraction involves minimal environmental and social impacts [169]. However, multi-step solvent extraction processes can lead to significant losses of lithium, affecting economic feasibility and recovery efficiency, which are influenced by market pricing and metal price fluctuations [170]. The movement of metals in tailings usually influences hazards associated with human toxicity and ecotoxicity. However, the modeling of LCA frequently neglects the uncertainty, which poses challenges due to the complex nature of tailings. Novel methodologies, such as utilizing tailings in construction materials, are gaining popularity. Incorporating mineral resource dissipation into LCA indicators could enhance sustainable tailing management by considering the depletion of finite mineral resources [171]. Existing studies on energy consumption and greenhouse gas emissions in LCAs have focused primarily on isolated supply chain stages, underscoring a research gap in comprehensive environmental analysis [172,173]. The lack of systematic studies on recycling key critical minerals highlights the need for a deeper understanding of the global mineral cycle.

Advanced techniques for recovering resources from acid mine drainage, including the extraction of metals, sulfuric acid, and REEs, rely on purification, treatment, and utilization technologies (Figure 15). Processes like acid retardation and electrodialysis are commonly used to treat H_2SO_4 while chemical, biological, and electrochemical methods are employed to recover metals and REEs. However, high operational costs remain a significant challenge, especially as solvent evaporation during repeated extraction phases undermines economic viability [174]. The economic viability of leaching methods lies in their ability to extract valuable metals from tailings that would otherwise be discarded as waste. For instance, the recovery of rare earth elements from tailings generated during iron ore processing has been demonstrated as a cost-effective strategy, as described in the work of Jordens et al. [108]. Additionally, the adaptability of leaching to handle low-grade and complex ores makes it a valuable approach for addressing the resource scarcity of critical minerals.

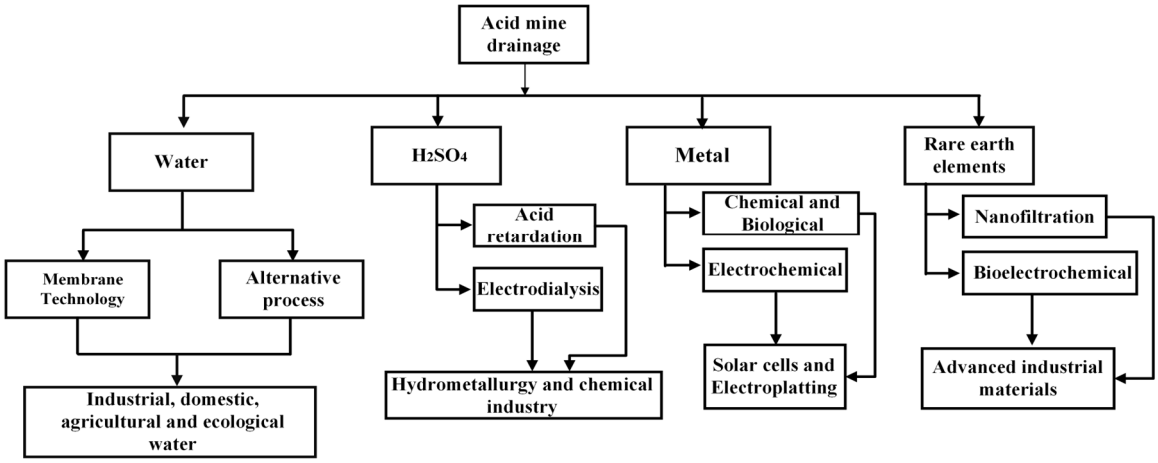


Figure 15. Resource recovery strategy from acid mine drainage [175].

From an environmental perspective, leaching methods offer several advantages. By processing mine tailings, they reduce the need for primary mining, lowering the environmental impact associated with land disturbance and ore extraction. However, challenges remain in managing the chemical reagents used in leaching, particularly in acid leaching, which can produce toxic effluents. Advances in waste treatment technologies and the development of greener leaching reagents, such as organic acids and ionic liquids, are helping address these challenges.

The mining sector is predicted to produce 19 billion tons of solid tailings by 2025, which presents significant environmental concerns in the areas of water use, waste management, and dam safety. Reusing and recycling water is crucial to reducing the negative environmental impacts of tailing reprocessing. Even with the advancements in technology like as electrodewatering and deep cone thickening, efficiency continues to be restricted by clay components, particularly in the case of large flow volumes. In order avoid long-term hazards and ecological catastrophes, managing tailing dewatering and mine water treatment and recycling is essential. Technologies like integrated chemical processes and bio-based polymers show potential for improving dewatering while reducing environmental damage. More investigation into sustainable, affordable techniques is required for water conservation and appropriate residue management. Furthermore, mining companies must sustain financially viable recycling activities while ensuring effective mineral processing by establishing a balance between the costs and benefits of water reuse. These costs can be increased by qualified workers, modern treatment methods, and facility maintenance [176].

Figure 16 displays treatment methods that are preferred for their cost-effectiveness, low capital, and operating costs. These methods include membrane separation, ion exchange, oxidation, adsorption, bioremediation, precipitation, coagulation/flocculation, and electrochemical techniques like electrocoagulation. The advanced treatment of mine water ensures compliance with quality guidelines and removes impurities that could hinder the effectiveness of tailing reprocessing. Effective treatment not only reduces environmental impact but also enhances processing performance by reducing issues such as corrosion and scaling [177–181]. A study by Matebese et al. has highlighted several effective mining wastewater treatment methods, including SAVMIN®, SPARRO®, Biogenic Sulphide, and DESALX®, which can recover over 95% of the water for reuse. While current methods for removing metal show potential, managing toxic sludge and ensuring economic feasibility are still challenging. More research is necessary to explore how adsorbents and adsorption techniques can be used to treat mine wastewater. Creating circular mine water systems will require combining these technologies to extract valuable metals from diluted solutions and generate clean water.



Figure 16. Cost-effective methods for mine water treatment.

5. Future Directions, Opportunities, and Conclusions

The global transition to low-carbon economies relies heavily on renewable energy technologies and energy efficiency improvements, both of which demand essential metals. Reprocessing mine waste to recover critical minerals is a key strategy for advancing a

circular economy. This approach not only minimizes waste through reusing, recycling, and reprocessing materials but also addresses the challenge of declining ore grades over time [182]. Evaluating the financial viability of tailings reprocessing involves a detailed analysis of mineral concentrations, which are often site-specific and heavily influence economic potential [183]. The effective recovery of critical minerals depends on geological, mineralogical, and hydrological conditions. Factors such as the particle size, texture, crystal structure, and degree of mineral liberation are crucial for developing a processing plan. These elements impact the selection of recovery methods, which should aim to optimize costs and minimize environmental impacts. Understanding the physical, chemical, and mineralogical properties of tailings is essential for assessing the economic feasibility of recovery based on current metal prices.

Regrinding partially liberated particles can enhance recovery but is less effective for very fine particles [75]. Secondary recovery processes differ from primary processing due to variations in the chemical and physical properties of tailings compared to the original ore. Tailoring recovery strategies to the specific characteristics of tailings is crucial. For instance, hydrometallurgical and bioleaching methods are effective for low-grade sulfidic ores while pyrometallurgical approaches are suited for high-grade ores. Incorporating bioleaching can offer significant economic, social, and environmental benefits [184]. An integrated strategy for recovering critical minerals from mine tailings is illustrated in Figure 17. Primary ore processing involves flotation, dewatering, conditioning, grinding, and crushing. The choice of processing techniques is influenced by factors such as the ore body, mining methods, and chemicals used, including collectors, flocculants, and frothers [185]. Thickening tailings before processing offers benefits such as water and reagent recovery, increased tailing density, reduced storage needs, and minimized acid mine drainage potential by decreasing permeability. Bioleaching, applied after filtering, uses microorganisms to recover minerals, providing an environmentally friendly solution for low-grade ores.

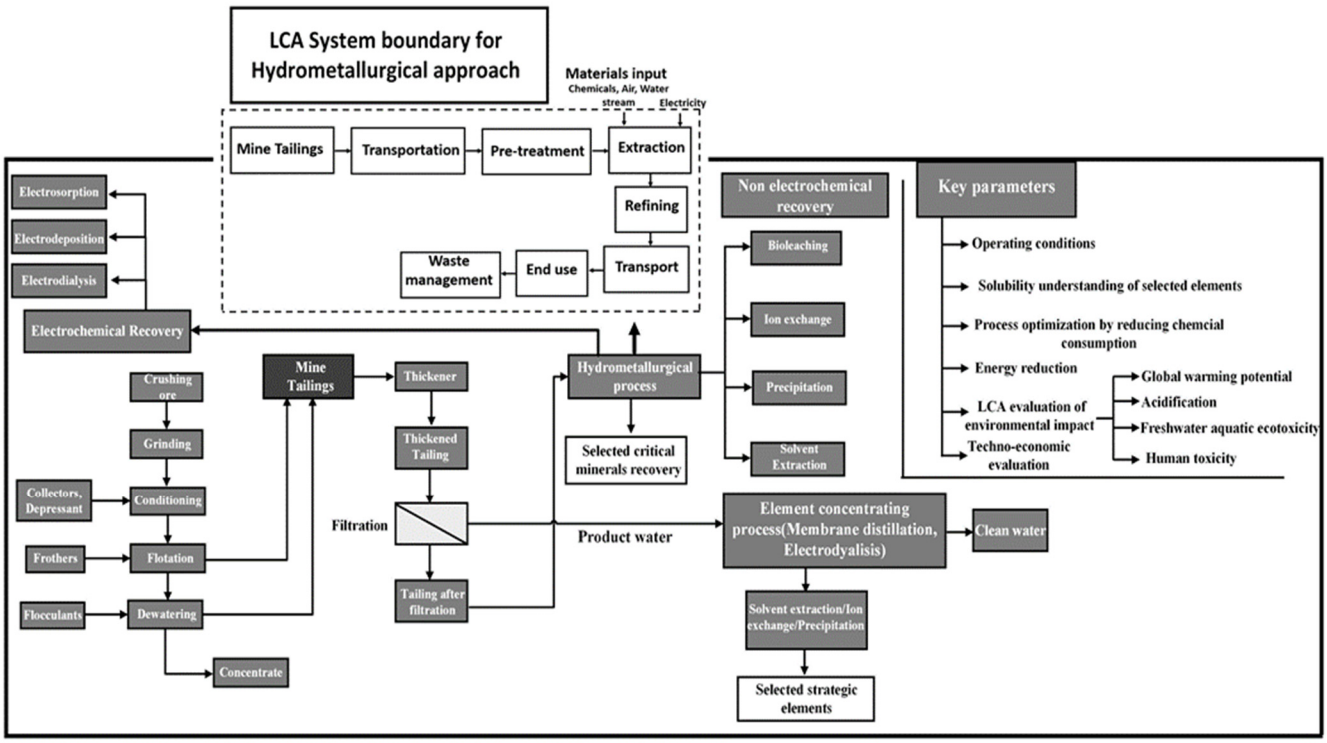


Figure 17. An integrated roadmap for the recovery of critical minerals along with important factors to consider enhancing the recovery process.

Mine tailings often contain toxic materials that must be separated during processing. For example, in zinc recovery from sulfide tailings, iron and arsenic must be removed due to complications they cause during solvent extraction. Successive hydrometallurgical recovery stages—such as aqueous leaching, ion exchange, precipitation, and solvent extraction—are necessary for separating these elements. Additionally, membrane distillation and electrodialysis can be used to obtain clean water from wastewater and recover remaining valuable minerals after filtration. Valorization strategies add economic value by transforming waste and residues from metal extraction, such as solvents and wastewater, into marketable products [2].

LCA is a powerful tool for evaluating process performance by defining system boundaries and assessing environmental indicators like acidification, global warming potential, and toxicity. LCA can quantify the chemicals used and their environmental effects during mineral recovery. The LCA system boundary for the hydrometallurgical process includes the phases associated with the extraction of selective critical minerals from mine tailings. The process starts with the transportation of tailings, followed by pre-treatment and extraction phases to prepare the materials for mineral recovery. Electrochemical (electrosorption and electrodeposition) and non-electrochemical (bioleaching and ion exchange) recovery technologies enable mineral extraction and refinement while controlling residuals for waste disposal. Following the extraction and purification of minerals, the process handles waste and generates both product water and mineral concentrates. However, current LCA approaches face challenges due to inadequate environmental databases, which limit comprehensive assessments of complex systems [186]. For instance, the GaBi database lacks information on chemical sources (e.g., H_2SO_4) and power consumption for industrial zinc production. These gaps should be addressed in future research. The integration of physical separation methods with secondary recovery techniques offers a comprehensive approach to maximizing resource recovery, particularly for critical and rare minerals.

The circular economy framework is crucial for managing waste generation and resource allocation, particularly as ore grades continue to decline. Recent advancements in the circular economy approach for critical materials, such as rare earth elements, nickel, cobalt, and lithium, have underscored innovative recycling methods and the importance of sustainable resource management to meet the rising demand fueled by clean energy technologies. A primary concern in traditional extraction and recycling processes is the reliance on expensive and environmentally harmful chemicals, such as potent acids, which can have adverse environmental and economic impacts [187]. A closed-loop strategy, as depicted in Figure 18, can enhance process scalability, optimization, and the mitigation of issues like acid mine drainage. In this model, recovered critical minerals are incorporated into value chains for sectors such as electronics, renewable energy, and advanced manufacturing. Efficient recovery from mine tailings presents a unique opportunity to reduce waste and alleviate the strain on natural resources, fostering a sustainable recovery cycle. Post-consumer recycling further reintroduces these critical minerals into the manufacturing system, reducing reliance on virgin material sources and minimizing environmental harm. This dual strategy of recovery and recycling embodies the principles of a circular economy, promoting sustainability and resource efficiency. Despite technological advancements, numerous challenges persist in the widespread adoption of circular economy principles for critical materials. One major hurdle is the scalability of recycling processes to meet projected demand. The International Energy Agency (IEA) has highlighted that the global clean energy transition will require a substantial increase in the supply of materials like lithium, nickel, cobalt, and REEs [188]. Meeting this demand through sustainable means necessitates further technological innovation, robust policy frameworks, and the development of closed-loop supply chains. Another challenge is the complexity of extracting

these metals from mixed-material components. Unlike traditional recycling, which focuses on straightforward material recovery, advanced recycling must contend with intricate product designs and varying material compositions. Overcoming these barriers will require sustained investments in research and development and the establishment of industry standards for eco-design and recyclability.

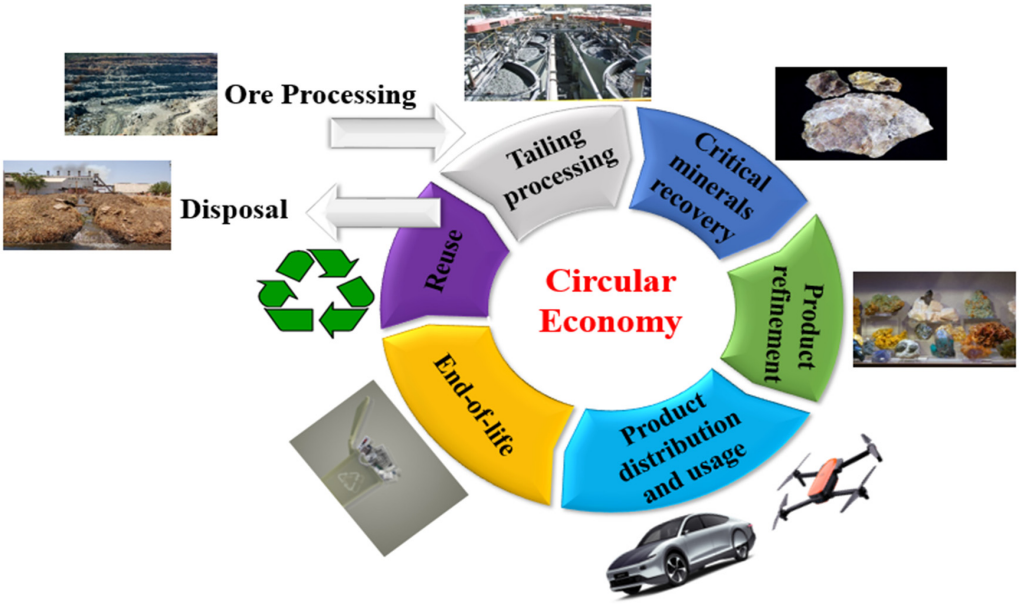


Figure 18. Suggested circular flow diagram for critical minerals from ore processing to disposal [189].

Achieving the sustainable production and supply of critical minerals involves community awareness, repurposing mining sites, and enhancing domestic supply. Boosting domestic recovery from unconventional sources like mine tailings could reduce the need for new mining sites, contribute to economic stability, and support national security. However, foreign trade policies can influence mineral prices and mining activities generally incur environmental costs. Employing eco-friendly recovery strategies can mitigate these impacts, though some environmental considerations must be addressed carefully. Figure 19 outlines a strategy for sustainable mineral production and supply.

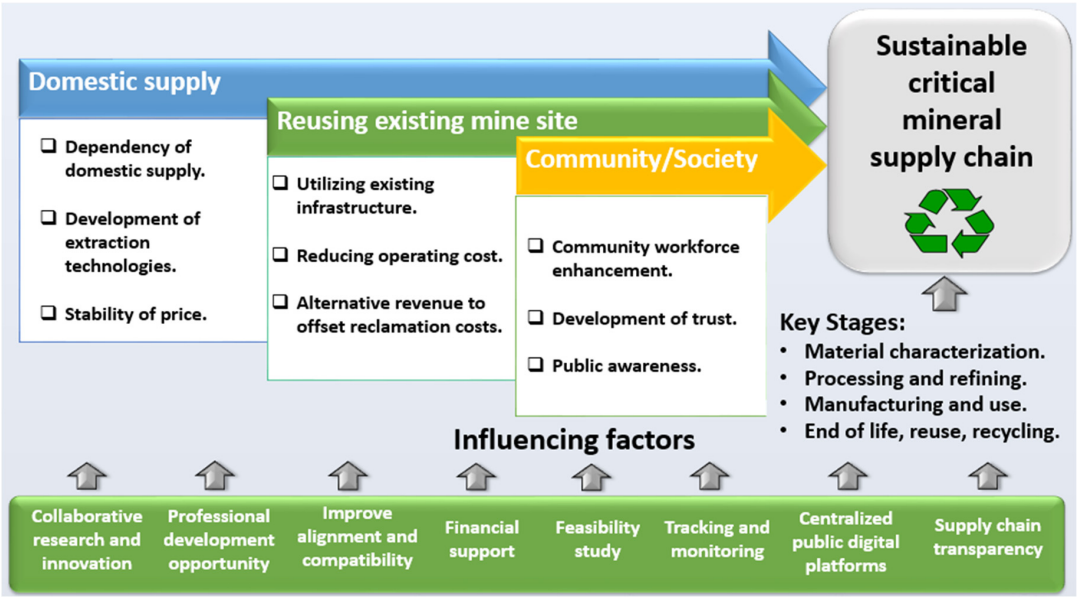


Figure 19. Sustainable critical mineral supply chain framework.

Utilizing current mine site infrastructure can also help extract important minerals from tailings, cutting down on expenses for crushing and processing. This strategy could be more cost-effective than traditional mining and could lead to the creation of jobs in the area while also building trust with stakeholders. Successful extraction requires continuous research, training, financial support, and public education. Additionally, accessible financial policies are needed to encourage investment in the critical mineral supply chain (Figure 20).

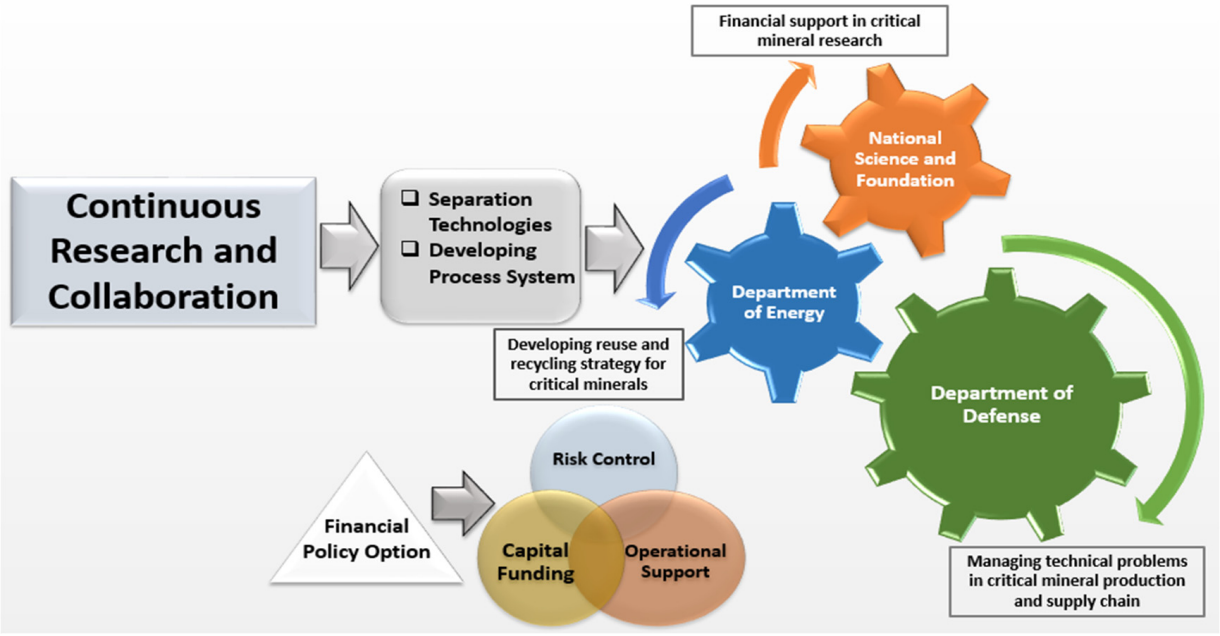


Figure 20. Critical mineral research and collaboration support by federal agencies and promoting policy options.

The process of mineral production is a complex system that involves resources, environmental impacts, and sustainability goals. In Figure 21, the process starts with extracting minerals from the earth, which requires a lot of energy, land, water, and chemicals. However, this extraction has negative effects on the environment such as water shortages, air pollution, soil degradation, and carbon emissions. These impacts can be influenced by factors like the type of ore being mined, waste management methods, and energy consumption. After extraction, minerals go through processing to recover valuable components. The chemical processing can create emissions that contribute to issues like acidification, human toxicity, and global warming. The process produces not only desired minerals but also a significant amount of mine waste. To reduce environmental impacts and promote sustainability, it is important to prioritize practices that focus on preserving resources, improving energy efficiency, reducing emissions, and following circular economy principles.

Implementing strategies such as waste reduction, resource recovery, and innovative technologies can greatly reduce the environmental impact of mineral production. Sustainable mineral production is essential for promoting resource efficiency and supporting a circular economy. By adopting environmentally friendly practices, mineral extraction and processing can meet society's growing demand while minimizing environmental impacts and preserving the planet for future generations.

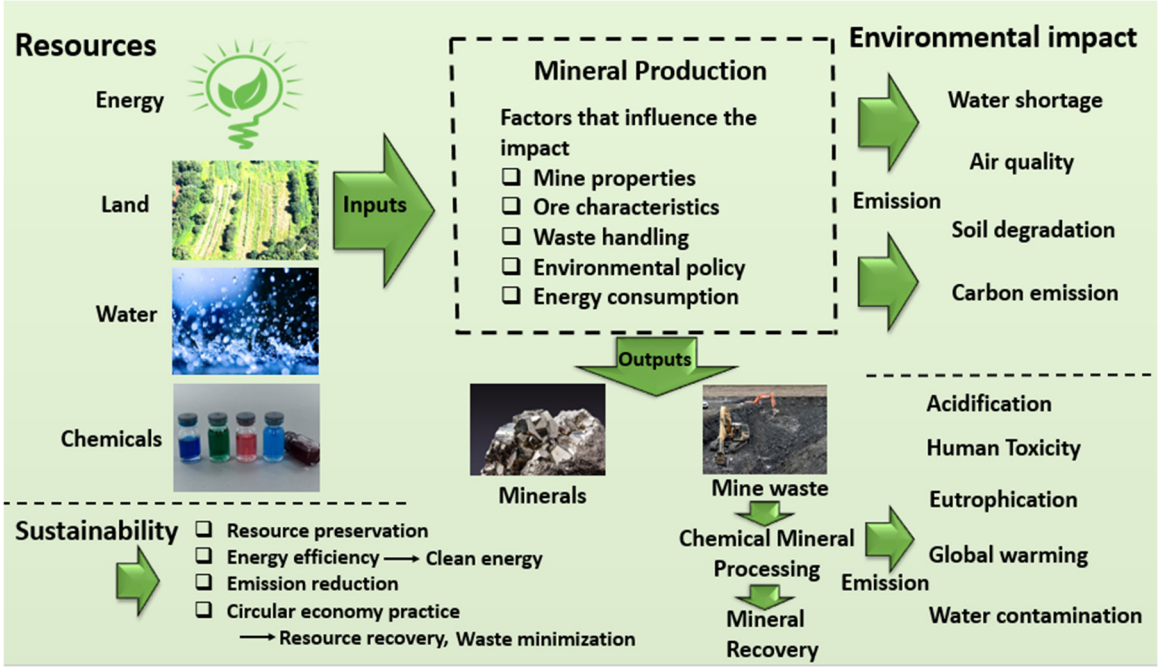


Figure 21. Sustainable mineral resource management.

Overall, this review article comprehensively has examined selective metal sources, mine production, and extraction technologies used to separate essential minerals from mining tailings and environmental consequences. Additionally, it proposes some recommendations for a sustainable mineral recovery and production strategy. The followings can be concluded for future research:

- Conventional hydrometallurgical techniques, such as solvent extraction and acid leaching, are resource-intensive, costly, and complex, necessitating further research for optimized and cost-effective methods for extracting valuable and hazardous minerals from mine tailings.
- Bioleaching can be a potential method for reprocessing mine tailings, offering economic and environmental benefits, but its low recovery rate and excessive heat generation necessitate further research. Bioleaching may also have higher freshwater and human toxicity impacts than the landfilling of mine waste, depending on the metals involved in the process. Therefore, comparing elution experiment analyses between bioleaching residue and acid mine drainage can be a promising new research area.
- The alternative hydrometallurgical process chain can be a viable option for recovering selective economic minerals from mine tailings, with higher efficiency influenced by pH and requiring less electricity than traditional industrial production.
- Reducing processing costs can be achieved by reducing chemical usage, transitioning to automated systems, and using geothermal energy as a fuel source for process optimization. Further research is needed to explore economic possibilities of reprocessing tailings through integrated resource recovery techniques and clean water production.
- The circular recovery of critical minerals from mine tailings can promote sustainability and reduce environmental impact. The closed-loop strategy can enhance process scalability and optimization while mitigating acid mine drainage.
- Research on eco-friendly alternative chemicals such as ammonia and ammonium salts, along with the integration of hydrometallurgical processes (acid leaching, solvent extraction, precipitation) and bioleaching, can be crucial for the efficient extraction of valuable minerals.

- Phytomining is another innovative metal recovery method that uses plants to extract specific metals from soil and tailings. This eco-friendly method can minimize ecological impacts and disruption in extraction processes, contributing to a circular economy.
- Since solvometallurgy is the only technique for extracting metals that employs solely non-aqueous solvents and no water, it must be used on a huge industrial scale. Direct solid leaching and non-aqueous slurry solvent leaching are two possible methods for completing this operation. The primary benefit of solvometallurgy is its lower cost compared to other traditional processes due to its reduced energy and water usage. However, ionic liquids must be carefully considered when using a solvometallurgy technique since they are more costly than molecular solvents.
- Developments in selective sorption technologies, low-energy electrochemical recovery methods, green mining technologies aimed to minimize mine waste, and state-of-the-art sensor technologies for accurately evaluating mineral composition can serve as impactful strategies for sustainable mineral recovery from mine tailings.
- However, sustainable recovery also requires collaboration, intensive research on technical and economic feasibility studies for the production of critical minerals, and strict adherence to regulations.
- Prioritizing educational outreach, investing in research, and developing the workforce are essential for a future that emphasizes environmental awareness, resource efficiency, and the establishment of a sustainable supply chain for critical minerals in the mining industry.

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