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Sustainability challenges of clean-energy critical minerals: copper and rare earths

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The transition to a clean-energy economy in an effort to mitigate climate change has brought a need for intense mining exploration of a critical class of minerals, previously mined and used at a fraction of what is required today and for the upcoming decades. For some common metals, such as copper, major deficits are forecasted for 2030, and for some less common ones, such as rare earths, mined quantities have recently increased 32 times relative to those in the mid-1950s and are expected to increase sevenfold from current levels by 2040. This situation is expected to become more severe given the long time span needed for exploration of new sites, the declining ore grade of existing mines, the geographical distribution of these minerals and the environmental degradation caused by mining and mineral processing activities. It becomes, hence, critical to improve existing mining operations vastly, reduce waste volumes and fresh water use, reduce environmental impacts and recover increased quantities of minerals from mine tailings, as well as from the recycling of post-production products. This paper focuses on copper and rare earths to expound on their exploitation issues, their processes, the sustainable utilisation of mineral waste and tailings and their recovery from end-of-life consumer and industrial items.

Keywords: clean-energy minerals/copper waste utilisation/end-of-life product recycling/mine tailings/rare earths/UN SDG 6: Clean water and sanitation/UN SDG 7: Affordable and clean energy/UN SDG 15: Life on land

Introduction

The need for climate change action has accelerated the deployment of clean-energy technologies with their mineral requirements having increased 50% since 2010. The International Energy Agency (IEA) has assessed that five minerals, copper (Cu), lithium (Li), cobalt (Co), nickel (Ni) and rare-earth elements (REEs; a family of 17 silvery-white, soft, heavy metals), are and will be playing a prominent role in the transition to clean-energy technologies (IEA, 2022). These 20 minerals (with the exception of copper) are also included by the US Geological Survey (USGS) in the list of 50 minerals that have been deemed as critical for the national security and economic development of the USA. Fuel minerals (including uranium) are excluded from this list (IEA, 2023). The downside to a clean-energy transition is that many more materials are required, compared with those for the current fossil-fuel-based energy economy. The IEA makes this point succinctly by stating that '[a] typical electric car requires six times the mineral inputs of a conventional car and an onshore wind plant requires nine times more mineral resources than a gas-fired plant of the same capacity' (IEA, 2022: p. 28).

Intensification of mineral exploitation to meet the needs of a clean-energy economy brings a host of new problems. These include the geographical distribution of the needed minerals, which are more concentrated in certain regions and countries than oil and gas. In terms of global copper reserves, about 23% of them are found in Chile, 10.5% in Australia and about 9% in Peru. About 44% of nickel is found in only two countries, Australia and Indonesia, followed by Brazil with 17% and Russia with about 8%. Approximately 46% of cobalt is in Congo, 18% in Australia, 6.5% in Cuba and with less than 2% in each of the next three countries. Of rare earths, 37% are in China, about 18% in Vietnam, 17.5% in Russia and the same percentage in Brazil. Finally, about 42% of the lithium reserves are in Chile, 26% in Australia, 10% in Argentina and 7% in China (Figure 1) (USGS, 2022). In all of these critical metals, Europe and the USA appear to represent a very small fraction of the global reserves, which is perhaps reflected by the fact that the number of metal mines that were active in the USA had steadily declined from 940 in 1983 to 270 in 2021 (CDC, 2023). On the other hand, continuing mineral exploration revises the currently known landscape of mineral reserves significantly. Thus, in terms of lithium, the project in Thacker Pass, Nevada, which was approved in 2021 by the Bureau of Land Management, US Department of the Interior, is estimated to tap 4.08 million metric tonnes (MMT) of lithium carbonate equivalent reserves with a mine life of 40 years and 5000 acres (2023 ha) of land to be disturbed (Lithium Americas, 2023). Only this site places the USA just behind Chile's 9.2 MMT and Australia's 5.7 MMT of estimated lithium reserves (USGS, 2022). Associated with the above is the fact that mining projects take on an average over 10 years from initial discovery to production, which in poor regions where many of the clean-energy minerals are found is projected to extend longer, due to the lack of infrastructure, technological know-how, regulatory gaps and security issues.

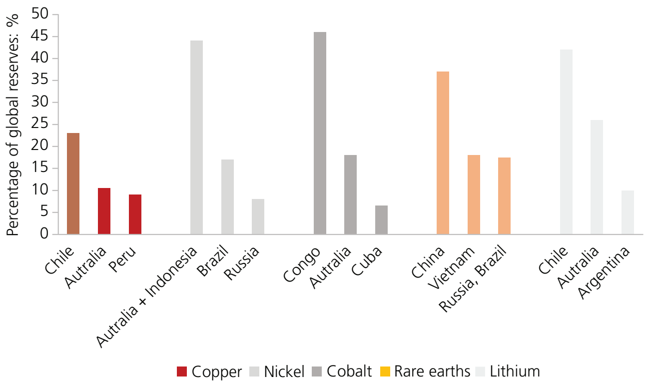

Figure 1. Geographical distribution of critical minerals (data by USGS (2022))

Other significant challenges of the increased extraction and production of clean-energy minerals include, among others, the depletion of water resources; the pollution of air, water and land; and the effect on land use and well-being of ecosystems. Mineral mining drilling, extraction and processing with their high water volume requirements will task the water resources of many countries, particularly in areas that are water stressed. This aspect is directly related to the majority of the targets (targets 6.1, 6.3, 6.4, 6.5 and 6.6) set for UN Sustainable Development Goal (SDG) 6, clean water and sanitation. The IEA (2022) indicates that 50% of the current copper and lithium production takes place in water-stressed regions, such as Australia, northern Chile and the desert south-west of the USA. Water requirements to extract 1 t of lithium are about 500 000 l (Tedesco, 2023), which corresponds to the water consumption of about 850 people per day in the USA (average water consumption per person per day in the USA was 156 gallons (591 l) in 2020 (CDC, 2020)). In Chile, where the largest lithium reserves are found and where the 2016 water allocation was 50 l per person per day, this volume of water to extract 1 t of lithium corresponds to 10 000 persons' water consumption, daily (OHCHR, 2020). In certain areas in Chile, where mines have depleted the tapped local surface water and groundwater, operations have accelerated improvements in water recovery from tailings and the use of seawater (Cacciuttolo and Atencio, 2022). Associated with the above is surface water and groundwater pollution as a result of, among others, tailings ponds, commonly used to store mining waste, and acid mine drainage (AMD), which can persist long after closure of a mine (de Oliveira Bredariol, 2022). Extension of the mining activities to extract the needed minerals for a clean-energy economy may bring land use changes and threats to ecosystems, an aspect referred to in UN SDG 15, life on land, to the point that some authors have questioned how environmentally friendly 'clean' energy really is (Bosler, 2021).

Thus, the transition to clean-energy technologies, as stipulated in UN SDG 7, affordable and clean energy, brings up the need for a more sustainable approach to mining; the intensification of recycling efforts, particularly in targeted metals; and the development of processes that are more energy, water and material efficient. In particular, the utilisation of waste minerals can bring several benefits to mining operations, including the following.

- Reduced environmental impact. By utilising waste materials, mining operations can reduce the amount of waste sent to disposal sites, thus reducing their environmental impact.
- Resource conservation and cost savings. The utilisation of waste minerals can reduce the need for virgin materials and can provide a cost-effective source of raw materials for industrial processes.

This paper focuses on copper and rare earths with the remaining critical elements to be addressed in a later paper. The exploitation issues of critical minerals are presented here and related to UN

SDGs 6, 7 and 15, which include, among others, the environmental challenges of mineral mining and the sustainable utilisation of mineral waste and tailings, as well as the current state of and future trends in processes and recycling, with the focus of this study being on copper and rare earths. These topics are expounded in the subsequent sections.

Environmental challenges of mineral mining

The mining industry plays a major role in the economies of many countries across the world. For example, raw non-fuel minerals mined in the USA represented in 2021 a value of US$90.4 billion, with US$33.8 billion contributed by metals, US$27.4 billion by other industrial minerals and US$29.2 billion by natural aggregates. The value of metals and minerals products recycled in the USA reached US$43 billion in 2021 (USGS, 2022).

Nevertheless, the mining industry has long been associated with environmental degradation and depletion of natural resources (e.g. Liu *et al.*, 2019). Mining activities and metallurgical processes generate waste rock and tailings waste residues (TWRs), a by-product of natural ore extraction processes. The quantities of various classes of waste produced during mining operations are vast. For example, a large-sized copper mine generates 270 000 metric t of rock waste per day. About two-thirds of this is classified as non-economical fraction and disposed on site, whereas the remaining 90 000 metric t is mixed with 114 000 m^3/day of water to create a concentrate that is processed to extract minerals or metals (Roche *et al.*, 2017). After processing, TWRs, which include solids and the processing water together with chemical reagents, are set in constructed ponds where part of the water is recycled back into the extraction process. TWRs, in the form of slurry, are then pumped in nearby tailings waste facilities (TWFs) (Figure 2) and as dry layering of condensed TWRs on the ground surface. They remain there during the life of a mine (20+ years) and after closure. Due to the variety of physical and chemical processes that take place during mineral extraction, the particles of the TWRs are very fine and have large specific surface areas and, in general, are associated with clay minerals. Hence, tailings separation becomes a difficult task (Mohamed *et al.*, 2023).

Major environmental disasters involving tailings spills include the 2014 Mount Polley, British Columbia, Canada, failure of the tailings storage facility (TSF) dam at the copper and gold mine located there. This released 17 million m^3 of water and 8 million m^3 of tailings and materials, which included several metric tonnes of arsenic (As), lead (Pb), copper and nickel, among others, and which travelled about 9 km along the nearby channel and floodplain (Government of British Columbia, 2023). The emergency response and abatement actions were completed in September 2019 with effluent monitoring required past that date. The following year, on 5 November 2015, the Fundão TWF dam of the Mina Germano/Samarco mine (Figure 2) in the so-called Iron Quadrangle, located in south-east Brazil, collapsed, releasing 33 million m^3 of mine waste into the Doce River Valley, the fifth largest river basin in Brazil, travelling for 650 km and in the absence of measures discharged 17 days later in the Atlantic Ocean (Figure 3). Apart from the tremendous effect on the

Figure 2. Germano/Samarco mine, Brazil (Google Earth, 2023)

(a) (b)

Figure 3. Mouth of the Doce River, Brazil, at the Atlantic Ocean: (a) December 2015, after the Germano/Samarco mine tailings dam failure; (b) August 2023 (Google Earth)

environment, several towns along the path of the plume were engulfed and hundreds of houses were destroyed (Roche *et al.*, 2017). Proper engineering, monitoring and safety of tailings dams has become even more critical nowadays since the tailings-to-ore ratio has increased in the last decades, as a consequence of increasingly mining minerals from lower ore grades.

At the same time, mine tailings contain significant amounts of minerals and trace elements, and some mineral ores are known to have technologically enhanced naturally occurring radioactive material (Tenorm)-associated wastes. Naturally occurring radioactive material is defined by the US EPA as material that may naturally contain any of the radioactive elements, such as radium (Ra), uranium (U), thorium (Th) potassium (K) and their radioactive decay products, such as radium and radon (Rn). These, through mineral extraction, water processing and manufacturing, can result in the concentration of Tenorm waste (US EPA, 2023a). Mineral ores that are known to have Tenorm wastes include coal, copper, bauxite and alumina, and rare earths (US EPA, 2003, 2023b, 2023c). The radioactive elements contained in specific ores or wastes may be mobilised or leached by normal environmental processes. For example, uranium is soluble in the acidic waters associated with AMD and can also be mobilised in basic solutions. Process operations, such as '… acid or solvent extraction, electrowinning circuit unit operations, and furnace heating, first leach, then concentrate the radioactive materials in the product and waste streams …' (US EPA, 2003: p. 3). Thus, although mining activities at such a site do not necessarily imply that the generated waste '… is radioactively contaminated, but instead should be considered as an advisory that radiation may be present, and should be considered as a potential environmental hazard similar to the occurrence of heavy metals or acid mine drainage …' (US EPA, 2003: p. 2). Hence, extreme care should be exercised in the utilisation of mining waste.

Mining of iron sulfide-aggregated rocks, in the presence of water and oxygen, is known to produce acidic, sulfate-rich drainage, named acid mine drainage. Acid generation and contamination is conditional on the presence of (*a*) sulfide minerals; (*b*) a humid environment; (*c*) an oxidant; and (*d*) bacteria, which can accelerate the rate of acid generation (Akcil and Koldas, 2006; Geidel and Caruccio, 2000). Rock type influences the quality of AMD and plume evolution, with pyritic sandstones, for example, releasing their acid load rapidly, and argillaceous rocks tending to do this over longer time periods (Ziemkiewicz *et al.*, 1991). Primary sources of AMD include mine rock dumps; tailings impoundments; underground and open pit mines; pumped discharged groundwater; and construction rock used in roads, dams and so on. This makes the management of waste dumps, such as spoil piles, tailings dams and spent heap-leach piles, very critical since the potential exists for those to develop extremely acidic conditions (Akcil and Koldas, 2006). In particular, abandoned mines, such as those found in some European countries, with sulfide tailings contained behind old dams can be oxidised through exposure to the atmosphere, acidify, leak and pollute the environment (Figueiredo *et al.*, 2018). Apart from conventional technologies, such as water-treatment plants, there have been promising reports of applications in South Africa that rely on the deionisation of solutions that can treat AMD and produce commercial products, as well as the use of partially treated AMD to grow fruit and olive groves with very promising results (Akcil and Koldas, 2006). Wetlands constructed to receive AMD have also been used in several countries to remove pollutants from water and produce clean water for reuse (Pat-Espadas *et al.*, 2018; Wildeman *et al.*, 1991). Johnson and Hallberg (2005) summarised the methods used to remediate AMD, which include abiotic techniques (anoxic limestone drains and aeration and addition of lime) and biological methods (wetlands, permeable reactive barriers and packed bed iron (Fe)-oxidation bioreactors).

Copper mining and production

Copper mining

The total copper mine production in 2021 amounted to 20.5 Mt in a mine capacity of 24.1 Mt, with copper reserves being about 880 Mt, identified resources on the order of 2100 Mt and an additional 3500 Mt of resources estimated as undiscovered (ICSG, 2020; USGS, 2022). Here the following USGS definitions (USGS, 2022) apply:

- resource: a concentration of a naturally occurring material in the earth's crust, where, in its form and amount, its extraction is deemed to be of economic interest
- identified resources: resources where the location, quality, quantity and grade are either known or can be estimated from specific geologic evidence; these include economic, marginally economic and subeconomic resources
- undiscovered resources: resources that are apart from identified resources, whose existence is postulated
- reserves: part of the identified resources that satisfies specific minimum physical and chemical characteristics, as well as economic considerations, and which can at present be mined.

Given the above and the fact that secondary copper production from recycled scrap is estimated to be 17% of the total copper production, it is highly unlikely that any shortages in copper will appear in the future (ICSG, 2020).

Global copper production (Figure 4) is dominated by Chile, which produced in 2021 about 5.6 MMT of copper, followed by Peru with about 2.2 MMT, China and Congo with 1.8 MMT each, the USA with 1.2 MMT and Australia, Russia, Zambia and Mexico with less than 1 MMT each (WEF, 2022). Recent news of the top ten copper mining projects in the world under progress have placed Chile at the top, in terms of copper value to be produced, with three sites located in Africa (Eritrea, Congo, Botswana) and one each in Australia, Brazil, Greece, Mongolia, Oman and Russia (McClelland, 2023).

Correspondingly, Chile is the largest producer of copper mining waste globally, generating about 800 MMT of mining tailings per year, following an exponential growth since the late 1960s (Cacciuttolo and Atencio, 2022). These authors have estimated based on government statistics that the total quantity of mining tailings generated between 1905 and 2022 in Chile and held in TSFs corresponds to 13 021 MMT or its volume equivalent of 8494 million m^3, with a total surface area occupied by TSF of 26 876 ha. The largest number of tailings (about 43% of the country's total tonnage) is found in the north, at Antofagasta, which, with its port, is a major hub for export of mined material. Interestingly, the region is arid, which puts water use for mining activities in severe competition with other uses in a water-scarce region. On the other hand, the geology of the area coupled with an average (over a 30-year record) precipitation of only 4.4 mm (DMC, 2023) may help hinder extensive subsurface contamination.

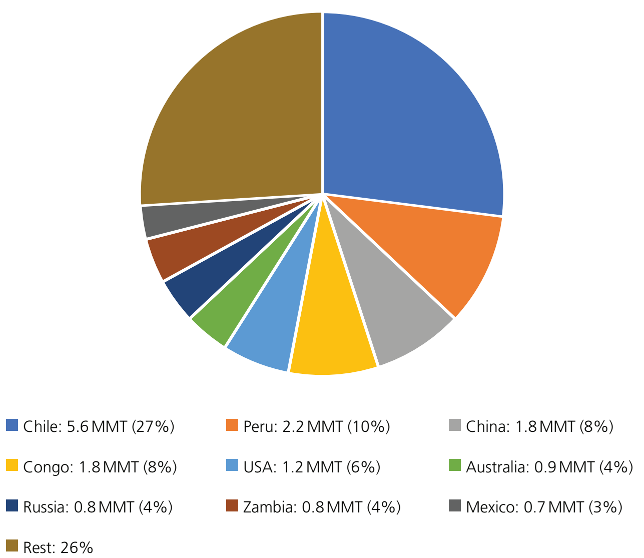

Figure 4. Global production of copper, 2021 (data from the World Economic Forum (WEF, 2022))

Primary copper production processes

The largest part of current copper resources is found in copper sulfide ores, which typically contain 1–3 wt.% copper. The copper production process is initiated by crushing and grinding of the ore to free up copper sulfide minerals. Copper is then concentrated through flotation. Here water and chemicals are utilised, making the ground copper sulfide minerals water repellent. Air that is passed through the mixture makes the copper sulfide minerals attach to air bubbles and float to the surface. Apart from copper, some other elements, such as iron and arsenic, exist within the crystal structure of the minerals, chemically bound at the atomic scale, thus requiring the application of physical and chemical processes to obtain high-purity copper (Schlesinger *et al.*, 2021).

For high-grade copper sulfide ores, the pyrometallurgical route (Figure 5) is typically followed. Thus, after flotation, roasting, an exothermic reaction, is employed, using oxygen to remove moisture and about 20–50% of sulfur (S) as sulfur dioxide, which is collected and converted to sulfuric acid (H_2SO_4). This is followed by smelting, where the copper concentrates are mixed with sand (silica) and limestone and melted to form matte copper, which contains the sulfide phase of copper and other metals. During this stage, most of the iron oxidises in the presence of silica to form a slag on top of the molten bath and is periodically removed and discarded. Matte ranges from 35 to 65% copper, with the copper content percentage referred to as the matte grade. The next stage,

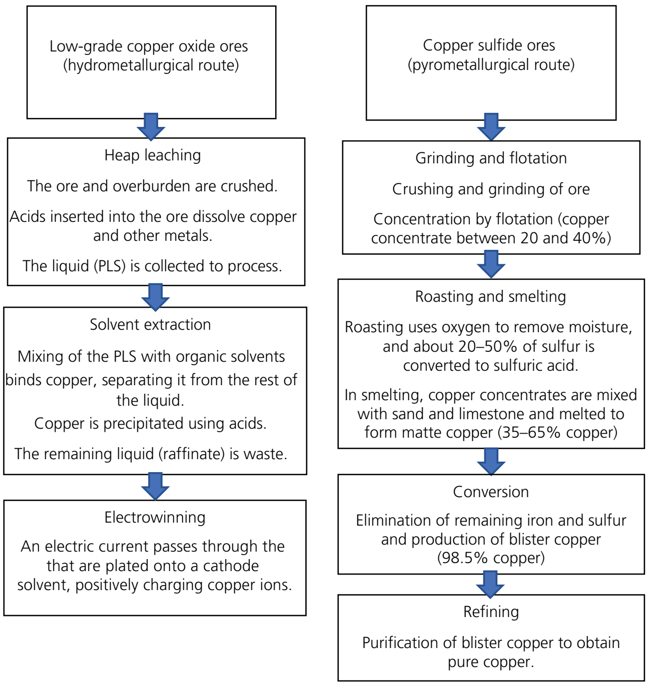

Figure 5. Primary copper production processes

called conversion, eliminates the remaining iron and sulfur present in the matte copper to produce blister copper, which is about 98.5% copper, and impurities, such as antimony (Sb), arsenic, bismuth (Bi), gold (Au), iron, lead, nickel, selenium (Se), silver (Ag), sulfur, tellurium (Te) and zinc (Zn). The last stage, that of refining, purifies blister copper to obtain pure copper. This is done through fire refining, where blister copper is melted in the presence of air into a 1100°C furnace with the impurities removed as slag and the copper oxide first subjected to a reducing atmosphere and then purified further by electrolytic refining. The latter separates copper from impurities by electrolysis in a solution containing copper (I) sulfate (Cu_2SO_4) and sulfuric acid to obtain 99.95–99.96% pure copper finally (Hawker *et al*., 2018; ICSG, 2020; Schlesinger *et al*., 2021; US EPA, 1986).

For low-grade copper oxide ores and unconcentrated low-grade sulfides, the hydrometallurgical route (Figure 5) is followed, starting with leaching. This, in its most commonly used form, named heap leaching, involves crushing of the ore and the placing of the smaller rock pieces onto specially designed pads. Acids are introduced into the crushed rock, and copper, other metals and potentially radionuclides leach out as a liquid, known as pregnant leach solution (PLS). The second method, in situ leaching, does not involve removal of overburden material but injection of chemicals through wells into the ore-bearing copper deposits. The PLS is collected in production wells and sent for further processing (Schlesinger *et al*., 2021; US EPA, 2023b).

The next process of solvent extraction involves the mixing of the PLS with organic solvents, which bind to the copper, separating it chemically from the rest of the liquid, and with the subsequent use of acids, copper is aided to precipitate from the copper-bearing liquid. Finally, electrowinning is used, which utilises electricity to extract copper out of the PLS (Schlesinger *et al*., 2021). The liquid that remains from this stage, the raffinate, which may contain Tenorm, is treated as waste (ICSG, 2020).

Notably, all of the above processes have been documented to have produced Tenorm at various copper mine sites in Arizona with in situ leaching, solvent extraction and electrowinning, as well as the recycling of the raffinate, to have resulted in the concentration of soluble radioactive materials. Samples taken at such sites have shown evidence of radiation of up to two orders of magnitude above background levels, in surface water, groundwater and soils, and mining processes and waste streams (US EPA, 1999). At the same time, the US EPA (2023b) has warned that pyrite and sulfide minerals found in tailings piles and exposed to air and water have the potential to leach radionuclides, which can be released to the environment through AMD from abandoned mine sites.

Rare-earth mining and production

Rare-earth mining

The demand for REEs is expected to increase sixfold by 2040 from current levels, and those for lithium and cobalt by 20-fold by 2050 (IEA, 2022). Rare-earth oxides (REOs) are used as catalysts, as automobile catalytic converters, in batteries for hybrid cars, in the glass and metallurgical and phosphor industries, in mobiles, in light-emitting diode lights and extensively in alternative energy systems and permanent magnet applications for electric motors and wind turbine generators (Goonan, 2011; Gupta and Krishnamurthy, 2005; Long, 2013).

REEs are subdivided into light REEs (lanthanum (La) and from cerium (Ce) to europium (Eu), or the elements in the periodic table with atomic numbers from 57 to 63) and heavy REEs (HREEs) (gadolinium (Gd) through lutetium (Lu), plus scandium (Sc) and yttrium (Y), or the elements with atomic numbers from 64 to 71 and 21 (scandium) and 39 (yttrium)). Principal deposits of REEs are found in carbonatites, which are within continental rift zones where melted mantle has been allowed to reach the surface. Most known carbonatites contain REEs at non-economic extraction concentrations. Alkalic igneous rocks also contain, usually, lower REEs, but their mineralogical complexity often questions their economic extraction (Long, 2013).

In terms of deposits that are economic to mine, REEs are usually modest in size with deposits containing HREEs being rare. Two sites with high (about 8%) REE concentrations include the Mountain Pass, California (Figure 6), and Mount Weld, Western Australia. The largest REE deposit in the world is in Bayan Obo, China, which makes China the dominant global REE producer in 2022 (Figure 7). Deady (2021) provides a world map of the known REE mines together with the type of geologic environment encountered in each.

Primary rare-earth production processes

Rare-earth ores are usually mined in open pits, where they are ground to free up most of the REEs from other minerals. Processing of REEs is usually done by flotation, gravity and magnetic separation techniques. Flotation, as discussed in the section headed ‘Primary copper production processes’, refers to the use of surfactants and wetting agents to separate minerals

Figure 6. Mountain Pass rare-earth mine, California (Google Earth Image, 2023)

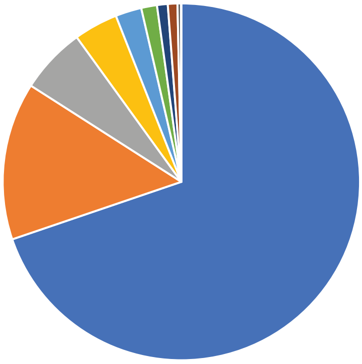

Figure 7. Global production of REEs, 2022 (data from Statista (2023))

from the ore by exploiting and enhancing their hydrophobicity/hydrophilicity (Orica, 2009). Thus, selective reagents are added in agitated tanks and adsorbed electrostatically onto the rare-earth mineral surfaces, allowing them to attach to air bubbles and float to the surface, where they are skimmed off as an REE concentrate, which is treated to extract and separate the various REEs. Remaining minerals are disposed of as waste. Details of the flotation electrochemistry mechanisms can be found, for example, in the paper by Anderson *et al.* (2017).

In many cases, as in two of the world's largest rare-earth mines, at Mountain Pass, California, and at Bayan Obo, China, heavy value rare-earth minerals coexist in an ore with low-specific-gravity gangue minerals (unwanted minerals that are also present in the ore), such as quartz. In such cases, gravity separation, which takes advantage of differences in the specific gravity of minerals to separate them, has been used. The most commonly used technique is using a centrifugal gravity concentrator, where the mineral slurry upon entering into a rapidly rotating bowl is subjected to centrifugal forces, which force the high-specific-gravity minerals against the sides of the bowl, becoming the REE concentrate, while the lower-specific-gravity minerals are moved with the fluid to the gravity tailings (Falconer, 2003). Magnetic separation, which is based on the behaviour of mineral particles under an applied magnetic field, is also used in mining processing, primarily for the removal of ferromagnetic gangue minerals and for certain paramagnetic rare-earth minerals (Haque *et al.*, 2014; Jordens *et al.*, 2014).

Recovery of individual REEs (Gupta and Krishnamurthy, 2005) is done by acid leaching of the REE concentrate, with the resulting solution processed through a large number of sequential steps, whereas the desired REE can drop out of solution as an oxide or hydroxide (in the case of cerium, with the addition of sodium hydroxide), or through solvent extraction, where a specific organic chemical is used, which allows the REE to pass into the organic phase and then the REO to be recovered from the leach solution by acid stripping (Long, 2013). Reduction of REOs to rare-earth metals, refining, is mostly done industrially by using chlorides as reductants with various technologies, such as electrowinning, electrorefining and solid-state electro-transport, being investigated (Gupta and Krishnamurthy, 2005; Opare *et al.*, 2021).

Mine tailings management, recovery and utilisation

Mine tailings management

Due to the facts that discovering high-ore grades to mine is becoming less prevalent and that large quantities of water, which is scarce at many mining sites, are needed for grinding and flotation, mining companies have invested in the application of tailings dewatering technologies to recover water, which can be reused back in the mining processes, as well as to speed up consolidation of tailings.

Water recovery and dewatering technologies applied to tailings and their efficiency depend on the particular tailings disposal scheme implemented at a particular site. The prevalent tailings disposal schemes produce tailings, which, based on their characteristics, are distinguished into (*a*) conventional tailings; (*b*) thickened tailings; (*c*) paste tailings; and (*d*) filtered tailings (Cacciuttolo and Valenzuela, 2022; Wu, 2020). Conventional or slightly thickened tailings, as in the case of copper tailings, may reach up to about 40% solid weight concentrations (Cw), and they are disposed in TSFs, which have large dams built either of the coarse fraction of tailings or borrow material. Conventional disposal results in segregation of the tailings during flow and their settlement as a flat deposit. For this type of tailings, water recovery can reach up to about 70%, with the water recovered by floating pumps or decant towers at the settling pond and by drainage and cut-off trench systems collecting dam seepage. The thickened tailings disposal (TTD) scheme consists of thickening of the tailings before discharge, for the case of copper tailings achieving up to 65% solid weight concentrations (Cw), which results in laminar non-segregating flow and a self-supporting deposit with sloping sides that requires only small dams. In the TTD method, a higher water recovery of up to about 80% can be achieved. The paste tailings disposal method produces a high viscosity, non-Newtonian fluid, characterised by paste copper tailings of 65–80% solid weight concentrations (Cw) and a water recovery rate of about 80%. This method has evolved from a technology that was used for subsurface backfilling (Bascetin *et al.*, 2016; Dixon-Hardy and Engels, 2007), and it requires high capital costs because of the positive displacement pumping needed to transport the tailings; on the other hand, large dams are not required. Finally, the filtered tailings method involves draining of the tailings until a solid material (called unsaturated cake) is obtained; hence, there is no need for large tailings ponds. The water recovery rate through this method can reach 90% and filtered copper tailings exhibit over 80% solid weight concentrations (Cw) (Cacciuttolo and Atencio, 2022). In economic terms, the thickened and conventional tailings technologies appear to be the most cost effective, with the filtered tailings technology being the costliest, except in situations where the use of seawater is required, in which case it becomes the best option of all (Cacciuttolo and Valenzuela, 2022).

Tailings disposal and management methods have been driven not only by technological advancements but also by regulatory requirements put in place to address TSF failures, the impact of earthquake events, environmental concerns and other aspects. Thus, Cacciuttolo and Valenzuela (2022) provide a detailed discussion of the TSF regulations in Chile that specify from Supreme Court Decree Number 86 of 1970 to Decree Number 248 of 2006, which specify the standards for the design, construction, operation, closure and monitoring of TSFs. The role of the state and comparison of key mining states' tailings-related legislation are expounded in chapters XIII and XIV of the book by Oberle *et al*. (2020), and a reader interested in the topic can consult this and other sources.

Recovery of copper and rare earths from mine tailings

The fact that old copper mine tailings have a copper grade between 0.2 and 0.3%, which is comparable with that of low-grade ores, has led to the exploration of technologies that seek to extract valuable metals from such and other metal tailings (Godirilwe *et al*., 2021).

Bioleaching is a technique for recovering metals from low-grade ores and mineral waste with the use of microorganisms, which is environmentally friendly and does not produce toxic waste (Bosecker, 1997; Rawlings and Johnson, 2007). Examples of the use of bioleaching in experimental studies include the following. Mulligan *et al*. (1999) used the *fungus Aspergillus niger* to investigate the bioleaching of an oxidised mining residue, of mainly copper, and concluded that a maximal removal of up to 60% of copper could be achieved. Iron- and sulfur-oxidising microorganisms are used in stirred tank reactors (STRs) to treat pyrite-rich tailings to retrieve cobalt and other valuable metals (Mäkinen *et al*., 2020). Ahmadi *et al*. (2015) showed that 55.0% of copper, 98.2% of nickel and 59.5% of cobalt could be extracted from sulfidic tailings of an Iranian mine during shake-flask-leaching experiments with a mixed culture of moderately thermophilic microorganisms. Panda *et al*. (2015) used a mixed meso-acidophilic bacterial consortium of iron- and/or sulfur-oxidising bacteria to enhance recovery of copper (~92–96%) from a slag sample. Falagán *et al*. (2017) used a microbial consortium of thermo-tolerant acidophiles, *Acidithiobacillus caldus* and *Sulfobacillus thermosulfidooxidans,* in the mine tailings from two mines, one in Spain and the other in Serbia, to recover copper (84 to >90%). Experimental conditions included a temperature of 45°C, the addition of elemental sulfur and the imposition of anaerobic conditions with a pH of leach liquors close to 1. The results of this study indicated that bio-processing of mine tailings would have economic and environmental benefits. Zhang and Schippers (2022) used acidophilic microbial consortia of mesophiles and moderate thermophiles in shake flasks and STRs to bioleach cobalt and copper from mine tailings in Chile.

Several other techniques have been tested at the batch and industrial scales to recover minerals from mine waste. Yin *et al*. (2018) reported that the use of flotation on copper mine tailings at the industrial scale could recover copper at a profit and reduce environmental footprint. Figueiredo *et al*. (2018), for mine tailings from a mine in Portugal that contained arsenic, zinc, tungsten (W), iron and copper, used flotation and leaching to analyse the recovery of these metals. Godirilwe *et al*. (2021) found that mine tailings of about 0.3% copper content when subjected to high-pressure oxidative leaching yielded a high copper leaching rate of 94.4% with water used as a leaching medium. Leaching with hydrochloric acid and different types of organic acid as lixiviants was used to recover REEs from the calcination product of a coal coarse refuse (Ji *et al*., 2022), whereas leaching of zinc and copper from low-grade tailings in Spain, which has more than 733 million t of mine tailings stored in TSF, was analysed by Álvarez *et al*. (2021) with the use of two carbon-based materials, a commercial activated carbon and a commercial charcoal (VC). Finally, Araya *et al*. (2020) conducted a techno-economic feasibility analysis of data from 477 Chilean TSFs to assess the potential valorisation of mine tailings. The results of their study showed that although the net present value of vanadium pentoxide (V_2O_5) recovery from mine tailings was significant (US$76 million), this was low for REOs, making an investment in the recovery of REOs risky.

Mine tailings utilisation

Mineral processing waste has been used in at least 14 states in the USA as material in road embankments over the last 40 years. Mine tailings have been used in embankment and fill applications by local US highway agencies, with the condition to be evaluated for metal leaching potential (FHWA, 2016). Thus, mine tailings have been used in Alaska; gold mill or dredge tailings in California, Colorado, Idaho and South Dakota; copper tailings in Utah and Michigan; lead–zinc tailings in Idaho and Washington; and feldspar tailings in North Carolina (table 9-6 in FHWA (2016)). These tailings may also refer to the solid waste from the process of recovering uranium or thorium from an ore, which is crushed and processed mechanically or chemically, resulting in a sandy waste, which contains heavy metals and radioactive radium (US NRC, 2020).

Silicate, calcite and clay are contained in significant amounts in copper mining tailings, and they are also the raw material for manufacturing cement. Hence, several studies have investigated the use of such tailings at different percentages in concrete production (e.g. Onuaguluchi and Eren, 2012; Thomas *et al*., 2013). Such practice would have the advantage of minimising the space occupied for long time periods by mine tailings, tying heavy metals in concrete and hence reducing the potential for environmental pollution, as well as reducing the cement industry's needs for raw material and the various environmental threats posed by one of the most polluting industries in the world (US EPA, 2022). In this direction, Ghazi *et al*. (2022) investigated the use of copper mine tailings as a partial substitute for cement in concrete. It was found that the samples containing mining tailings exhibited, relative to control samples, a significant increase in compressive strength, resistance to chloride ion penetration that increased with time and leaching of heavy metals from these samples below US EPA allowable limits. Gou *et al*. (2019) stated that the use of tailings as replacement for both fine aggregate and cement reduced the workability of mortar or concrete, while the compressive strength of concrete increased with tailings utilised as fine aggregate. However, the compressive strength of concrete decreased as the content of tailings as supplementary cementitious materials increased. Furthermore, mining waste, such as tailings and slags, can be used in the synthesis of geopolymers, which are a sustainable alternative to conventional cement. Geopolymer synthesis involves the reaction of aluminosilicate materials with alkaline solutions and can utilise various waste materials as precursors. Recent studies have explored the potential of oil sands and mine tailings that contain such minerals to replace ordinary Portland cement (Rao and Liu, 2015). However, in terms of the copper mining waste, the US EPA (2023b) has raised the issue of the potential for the creation of Tenorm during mining and processes to recover copper and hence the threat from subsequent utilisation of copper mine waste in industrial applications.

In Australia, several research studies have explored the potential of utilising mine tailings as soil amendments, demonstrating the technical feasibility and potential environmental benefits of this approach. Research studies have used mine tailings to sequestrate carbon dioxide (CO_2) and produce stable mineral carbonates for use as aggregate materials in the construction industry (Mohamed *et al*., 2023), and some have explored the potential of utilising mine tailings in soil remediation, such as the removal of heavy metals from contaminated soil (Mohamed, 1997). For example, a study conducted in China showed that the use of iron-rich mine tailings as a soil amendment can significantly reduce the concentrations of heavy metals in contaminated soil (Mu *et al*., 2020). The uses of various mine waste and tailings in engineering applications is summarised by Lottermoser (2011).

Recovery of copper and REEs from consumer product waste

Recycling of the five essential minerals towards a clean-energy economy has met with mixed results at the industrial scale. Thus, copper, recovered from scrap, contributed about 32% of the US copper supply. The majority (about 80%) of this was utilised by brass and wire-rod mills, 15% by smelters and refiners, and the remainder by foundries and chemical and manufacturing plants. Recycled cobalt represented an estimated 24% of cobalt consumption in the USA, in 2021, whereas in terms of rare earths, the quantities recovered from batteries, permanent magnets and fluorescent lamps have been very limited. Lithium diversified supply, and security has come up as a major issue for battery suppliers and vehicle manufacturers, with strategic alliances being established between technology and exploration companies. A total of only 32 companies in the world recycle lithium batteries, of which ten are in Europe, seven in China, five in the USA, three in Japan, two in Canada and in South Korea, and one in Australia, Mexico and Singapore (Baum *et al*., 2022). Finally, recycled nickel accounted for approximately 52% of consumption (USGS, 2022).

Recent research efforts have concentrated on the recovery of valuable minerals, and in particular of the critical minerals, from discarded consumer products and from solid- and liquid-waste-management operations. As an example of the critical minerals in a modern smartphone, the list includes the following: the display contains the REEs of lanthanum, praseodymium (Pr), europium, gadolinium, terbium (Tb) and dysprosium (Dy); the electronics and casing include nickel; and the battery contains lithium, cobalt and nickel. Finally, the smartphone microphone contains nickel, whereas in the microphone and speaker magnets, nickel, gadolinium, terbium, dysprosium, praseodymium and neodymium (Nd) are employed, and in the vibration unit, neodymium, terbium and dysprosium are utilised (RER, 2023).

Thus, Barragan *et al*. (2020) implemented a combination of hydrometallurgical and electrochemical processes to recover 96 wt.% pure copper deposit and 81 wt.% pure antimony precipitate from electronic waste (e-waste). Choubey *et al*. (2021) used electrolysis to recover copper from scrap circuit boards of desktop computers. Xiang *et al*. (2010) used a bacterial consortium enriched from natural AMD to solubilise copper from waste printed circuit boards (PCBs) within 5 days, and Benzal *et al*. (2020) used a two-step bioleaching process to achieve copper recovery of 95–100% from waste mobile phones within 48 h. Paleologos *et al*. (2023) indicated that with the increase in incinerated waste in developed countries, the practice of recovering metals from incinerator bottom ash (IBA) and fly ash (FA) may become more widespread. In particular, the copper content in incinerated municipal solid waste (MSW) is significant in developed regions. These authors detail the processes practiced in Switzerland, whereby small pieces of heavy metals, particularly of copper and gold, can be recovered from IBA and FA.

Shimizu *et al*. (2005) recovered REEs from waste fluorescent lamps using supercritical carbon dioxide containing tri-*n*-butyl phosphate complexes with nitric acid (HNO_3) and water (H_2O). Supercritical fluid extraction is a technique that uses a supercritical fluid, a fluid in a state with properties of both gas and liquid, to dissolve and extract desired materials. Ion exchange has been applied to recover valuable metals from various types of mineral waste, including uranium mill tailings and electronic waste, using an ion-exchange resin that selectively binds to the desired metals. The resin is then eluted with a solution that releases the bound metals, which can then be further processed or purified. For example, Felipe *et al*. (2021) reported the use of a cationic-exchange resin to recover REEs from acid mine water from a closed uranium mine in Brazil. Electrochemical recovery is a technique for recovering metals from wastes using an electrochemical process where the metal-bearing waste is treated as the anode in an electrochemical cell and a metal cathode attracts and recovers the desired metal. For example, Jiao and Zhu (2011) applied this method to recover REEs using a caesium chloride (CsCl)-based molten system as solvent. These techniques are effective for recovering metals that are present in low concentrations or are difficult to extract using other techniques. At the same time, the use of non-polluting techniques to extract minerals from waste constitutes a challenge to scientists. One example of a clean and energy-efficient process, that of diffusion dialysis, was used by Hammache *et al*. (2021) to recover REEs in experiments with polymer membranes using diluted end-of-life (EOL) hard-disk drives as feed solutions. Li *et al*. (2021) through an electrodialysis technology succeeded in separating and concentrating REEs from waste water.

Recent experimental developments that are currently being tested for commercial pilot application include the use of bacterial organic acids to extract REEs from spent catalysts and phosphors and use of copper salts to extract REEs from the magnets of shredded electronic waste. Apart from the need for technological innovations, the logistical steps of collecting and dismantling EOL products that contain REEs and the product design make recycling difficult, and they all need to be resolved before meaningful quantities of REEs are to be recycled (Wayman, 2023). Finally, the mounting volumes of EOL consumer and industrial products, particularly of e-waste, of which only 17.4% were recycled in 2019 in officially managed and operated facilities, has brought to light the manifold health threats posed, particularly to the over 30 million children and women who are employed in dismantling electronic equipment in informal, unregulated spaces in low-income countries (WHO, 2021).

Summary and conclusions

The need to move towards clean sources of energy to address climate change has altered the landscape of mineral elements extracted and processed, until recently. Mining and production of critical elements for clean-energy technologies have increased severalfold, with mineral exploration having accelerated lately. However, significant challenges exist in meeting demand, which include, among others, the depositional distribution of these elements in only a few countries, creating as in the case of rare earths the dominance of a single source (China) in the world market; their allocation in arid and water-stressed regions, thus tasking limited local water resources even further; and their existence, in many cases, in regions where political instability and security issues may exist. Complicating the above picture is the environmental record of mining operations, which in many countries have led to land degradation and pollution of surface water and groundwater, as well as the inadequate utilisation of technologies to extract valuable minerals not only from mine tailings but also from their recycling from industrial EOL consumer and industrial products.

Given the needs for water of many economic sectors in the new, cleaner economy, water-management plans of proposed mine sites are recommended. These should include hydrologic analyses, as well as improved water recovery schemes from tailings. Some of the measures may include the transition from conventional to thickened/paste disposal technologies and the construction of desalination plants that can serve, among others, mining purposes. Environmental protection from mining and management of waste dumps is very critical since the potential exists for the development in them of strongly acidic conditions and the generation of AMD. In that respect, strong attention must be paid on the control and mitigation of AMD during mining operations and after mine closure to control water entry and the spread of pollutants in the environment.

Mine waste and tailings with minimal processing have been employed in various engineering applications. The use of mine tailings and waste as raw material for the construction industry, such as in concrete and bricks, appears as a promising direction, especially since their use appears to improve the mechanical properties of concrete. Additionally, mine tailings have the potential to tie heavy metals in the concrete and hence reduce threats to pollute the environment, as well as mitigate the extent of the cement industry's operations, which have established it as one of the most polluting industries in the world. Prerequisite to any utilisation of mine waste in various geotechnical applications is a careful analysis of their geologic origin, since tailings may contain naturally occurring radionuclides from the parent ore, which the mining and processing operations have the potential to have concentrated to above background levels. More emphasis must be placed on the development of efficient and economically viable technologies to extract valuable minerals from tailings, which in some cases contain grades comparable with low-grade ores.

Finally, attempts to recover and recycle critical minerals from consumer and industrial EOL products have been very limited. Several experimental studies have shown promising results, but this move needs to be intensified given the increased waste quantities generated, which, for example, for e-waste have increased by over 20% in 5 years. In particular, the dumping of e-waste in poor countries, which results in public health issues for women and children that are employed at unregulated facilities for their recycling, as raised by the World Health Organization, apart from being immoral, is also short-sighted since it does not contribute to a search for solutions to the problem.

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