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Towards the implementation of circular economy strategies: An overview of the current situation in mineral processing
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Abstract
Mining resources have played a leading role in the development of humanity, and the demand for these raw materials is expected to increase in the foreseeable future. In addition, new technologies also require the extraction of new critical materials. These trends pose various challenges as there is a limited supply of natural resources, and standard mining and mineral processing practices are associated with significant environmental impacts, such as waste generation, energy and water consumption, and CO₂ emissions. The circular economy (CE) has recently gained attention as a model to address such a complex scenario. This work analyzes the current efforts towards the application of CE in mineral processing. Although advances have been made, this review shows that the most significant material flows and environmental impacts occur near the production sites, which currently limits the closure of loops. Besides, mining industries are conservative regarding the adoption of new technologies or processing strategies, which is another hindrance to the implementation of the CE. Thus, and with few exceptions, while some sectors are already facing advanced stages of CE (namely, CE 3.0), the mineral processing field struggles to advance from the basic CE requirements (i.e, CE 1.0 to CE 2.0).

Keywords: Circular economy, mining, mineral processing, tailing, energy, water

1. Introduction
One of the great problems that modern society faces, resulting from both population and economic growth, is the continuous increase in demand for raw materials that include mineral resources (Nasrollahi et al. 2020). In this scenario, the mining industry has both technological and socio-political challenges. As mining deposits are exploited, the concentration of minerals decreases, which means that it is necessary to extract and process increasingly larger quantities of ore to obtain enough raw material resulting in an incremental consumption of critical resources as water and energy, and the generation of massive wastes, e.g., overburden, slags, leached ores and tailings. For these reasons, the mining industry requires technological alternatives to process minerals more efficiently, seeking to minimize the environmental impact of its operations (Sánchez and Hartlieb 2020). Furthermore, mineral products are consumed far away from the production sites, bringing an additional challenge to close the material loops.

To address the challenges mentioned about raw materials production, the concept of circular economy (CE) has gained strength in the formulation of policies as it aims in general terms to achieve economic development while respecting resource limitations (Schöggl et al. 2020). Unlike
the traditional linear economy of “extract, make, consume and dispose”, the CE approach seeks to respect environmental boundaries by increasing the proportion of renewable or recyclable resources, thus reducing the consumption of virgin raw materials and energy, refocusing and redesigning processes along the value chain. If properly implemented, a CE will also reduce emissions and loss of resources. Approaches such as ecological design, exchange, reuse, repair, restoration, and recycling of existing products and materials will play an essential role in maintaining the usability of products, components, and materials while preserving their economic value. However, a transition from linear to circular approach requires fundamental changes throughout the value chain, from product design and production processes to new business models and consumption patterns (Elia et al. 2020). Consequently, a substantial expansion of the knowledge base is needed to chart progress and identify where more work needs to be done to effect changes. Despite the current advancements towards a CE, more information is required to inform decision-making with a holistic perspective on environmental, social, and economic impacts. A better understanding of the production structures and functions, the consumption dynamics, the financial and fiscal mechanisms, as well as the triggers and pathways for technological and social innovations are needed. Given the conservative nature of the mining sector, these needs are most significant in the mining industry.

Studies comparing the actual scenario with the adoption of the CE measures until 2030 show that the CE measures will increase recycling, reducing (material efficiency increase), repair, and reuse compared to the actual scenario (Wiebe et al. 2019). Accordingly, the implementation of CE measures is forecasted to reduce the global material extraction by about 10% (i.e, 27% in metal extraction and 7% in nonmetallic minerals) compared to the current scenario, likely reducing employment in the resource extraction sectors. Thus, the effect of these measures in countries that export metals and nonmetallic minerals can be significant for their future development. Furthermore, it is worth noting that the mineral raw material value chain has a global scale, where recycling, repair, and reuse activities are not always carried out in exporting countries but rather in importing countries. On the other hand, the adverse environmental effects of mineral extraction and processing, e.g., the generation of tailings and the use of resources such as water and energy, occur in exporting countries, which makes it difficult to close the material loops. Also, as mentioned before, to the extent that mining deposits are exploited, the concentration of minerals decreases.

There is no consensus on the concept of CE. Alhawari et al. (2021) have recently published a compendium of various definitions on circular economy that different authors have proposed; some emphasized recycling, others on eco-efficiency and resource productivity, prolonging the useful life of products, and reducing the use of materials. In our case, we have adopted the latter approach since it applies better to the primary mineral processing industry.

The purpose of this work is to provide critical analysis of the current situation regarding the application of CE strategies in mining and mineral processing industries, specifically in the treatment of primary sources. An extensive quantity of novel and interesting articles has been
published about CE in the processing of manufactured and end-of-user sources; however, this article focuses on mineral processing.

In the first section, a brief overview of mining and mineral processing and CE is given. Then we address the application of CE to mineral processing, considering an overview of the reasons, problems, challenges, and opportunities in the implementation of CE specifically to the mineral sector. Some specific topics are analyzed, such as the use of water resources in areas of water scarcity, use of seawater, more efficient processes design, reuse of tailings, generation of residues with less environmental impact, application of biotechnology in tailing valorization strategies, among other issues. The analysis follows value retention options such as refuse, reduce, repair, recycle, among others, following those proposed by Reike et al. (2018).

2. Background

2.1. Mining and mineral processing

Mining is an essential activity for many low, middle, or higher-income economies. Based on the Mining Contribution Index (MCI) that considers the relative importance of mining to the economic life of a country, many low and middle-income countries, such as Suriname, Congo, Guinea, Bolivia, Perú, and Sudan, have high MCI resulting in a strong dependency on the mineral exploitation sector (ICMM 2018) (see Figure 1).

On the other hand, the Resource Governance Index (RGI) is an indicator that measures the quality of governance in the natural resource sectors as mining. Most of the top ten MCI countries have low RGI, revealing that, although resource extraction could be an economic driver, the benefits are highly likely flowing only to some companies or favored groups (NRGI 2017). Conversely, countries that can be considered upper-middle or higher-income economies show the highest monetary value of metals and minerals (Figure 1). The implementation of CE measures is predicted to reduce the global metal extraction and nonmetallic minerals by about 27% and 7%, respectively, compared to the current scenario, as indicated above. Hence, the impact of these measures in countries with high MCI and low RGI can be substantial for their future development.

Currently, according to their MCI, the top ten mining countries are China, Australia, Russia, the United States of America, India, South Africa, Indonesia, Canada, Brazil, and Chile, with market values between 626 and 33.5 $USD bn. Some of these countries have good RGI, such as Chile and Canada, but others have weak RGI, such as China and Russia. Figure 1 shows a map that identifies the top producer of iron, lithium, platinum, aluminum, gold, silver, copper, and zinc, together with the top RGI and MCI countries.
Base metals, such as aluminum, copper, zinc, and tin, are non-ferrous metals that have a wide range of industrial applications, such as components for alloys as brass, steel, and bronze and as the basis for the generation of structural constructions, among others. For the extraction of the base species from the ore, depending on the physical, chemical, and mineral characteristics of the deposits, two processing routes can be carried out: hydrometallurgy and pyrometallurgy (Botelho Junior et al. 2019) (Figure 2). Other resources as cobalt, PGMs (platinum group metals) and ferrous metals (nickel and iron) may be treated by pyrometallurgy after a concentrating stage.

In preparation for either hydrometallurgical or pyrometallurgical processes, mechanical treatment of the ores is needed, starting by crushing and milling to liberate the mineral species. Mineral concentration through physical or mechanical means (e.g., flotation, magnetic separation, dense media separation) may be further required, particularly in the case of pyrometallurgical routes (Figure 2). There is an economic justification for upgrading a mineral; for every ton of metal, less material has to be transported, smelted, or leached. Thus, the concentration stage lowers CAPEX and OPEX of metal production. Sometimes, this concentration step can be simple. For example, in the processing of nickel laterites, the coarse fraction from the feed is separated because it has a lower nickel content than the finer material (Meshram et al. 2019). The mineral concentrating operations generate a large amount of tailings and consume large amounts of energy and water (Donoso et al. 2013, Curry et al. 2014). In addition, concentration technologies can be used to reprocess tailings to obtain valuable components such as titanium or copper (Ghasemi et al. 2019,
Mackay et al. 2020, Zhang et al. 2020) or remove unwanted components such as sulfidic species to prevent acid mine drainage (Nuorivaara et al. 2019).

Hydrometallurgical processes can generate significant amounts of waste, mainly solid residues after leaching that can contain traces from the utilized leachant and chemically unstable solid species (Reichardt 2008, Li et al. 2013). One of the best-known examples of problems associated with leaching is the gold extraction using cyanide, which generates numerous cyanide-containing and cyanide-related species that remain in solid wastes and residual process solutions (Johnson 2015). After leaching, other environmental problems can be generated, such as the production of iron-rich toxic waste (goethite) that arises during the hydrometallurgical processing of zinc ores (Pelino et al. 1996, Sannia et al. 2001).

Although the mentioned environmental issues in leaching, the hydrometallurgical technologies have been important to reach cleaner processes in the mining industry due to i) usually require less energy than pyrometallurgical operations, ii) can be employed in the abatement of acid drainage from tailings (Rodríguez-Galán et al. 2019), iii) remove heavy metal and arsenic from wastewaters and tailings (Wang, Sun, et al. 2019), among other alternatives (Conard 1992).

On the other hand, pyrometallurgical operations encompass the processes of calcination, roasting, smelting, and refining. Because metal grades in the ore are typically low, direct smelting treatment is not economically feasible. For this reason, as was indicated, minerals must be previously concentrated. For example, in the production of zinc, the sulfide mineral named sphalerite is firstly processed by flotation and the obtained concentrate is subsequently roasted and converted to metallic zinc in several furnaces. In a similar approach, chalcopyrite, a copper sulfide ore, is also treated by flotation-smelting-refining. Pyrometallurgical operations can produce several
environmental problems, especially air pollution, due to the emission of toxic gases such as SO$_2$, and metals/metalloids particulate matter (Dimitrijević et al. 2009, Serbula et al. 2017, Adamczyk and Nowińska 2019). Also, pyrometallurgy is an energy-intensive technology that further contributes to greenhouse gas (GHG) emissions (Liddell et al. 2011, Kulczycka et al. 2016). Another pollution problem associated with smelting is the generation of slags that contain heavy metals (Agnello et al. 2018).

In summary, despite the essential benefits that mining can offer to the producing countries and the surrounding communities in which it operates, it also generates undesirable impacts for the environment and population that require treatments or mitigation strategies. Such impacts include the intensive use of energy, soil, and water, the emission of particulate material, the generation of polluting effluents with a high content of heavy metals and metalloids, among others (Adiansyah et al. 2015, Matinde et al. 2018).

The major types of waste produced during the mining stage are overburden, tailing, dust, and acid mine drainage (AMD). Overburden is the soil and rock material extracted to access the mineral deposits, whereas dust is released during overburden removal and ore transportation. Then AMD, also called acid rock drainage, can be generated by the passive leaching of sulfur species from the disposed rocks and tailings. In the beneficiation stage, flotation is the leading producer of tailings with fine particles (<300 µm) (Edraki et al. 2014). The small size of particles and the high content of sulfide mineral species are contributing factors that may result in AMD generation (Bellenfant et al. 2013, Bascetin A. et al. 2016, Carmo et al. 2017). It is estimated that there are around 3,500 active deposits of mining waste worldwide, mainly consisting of rock dumps and tailings, with an astounding generation rate of around 100,000 million tons per year (Starke 2002, Lébre and Corder 2015, Rankin 2015).

In chemical transformation stages, such as leaching and pyrometallurgy operations, depleted ore, slags, and gaseous species are the main wastes. Leaching is the principal operation that generates solid waste, which usually contains metal and metalloid elements. Slags and gaseous emissions (CO$_2$, SO$_2$, NOx, PCCD/Fs) are common wastes of pyrometallurgical processing.

The growing demand for metals has led to a progressive increase in mineral production from the mine, whether from those extracted in magnitudes of billions of tons such as coal and iron or those produced in smaller quantities such as gold and PGMs. However, it has been evidenced the mineral cut-off grades have decreased because of the decrease of valuable minerals (Figure 3a-d).

The scenario of increasing production and lower ore grade is bearable under two scenarios: on the one hand, an increase in the efficiency of the processes that allows greater use of resources and waste generated in the past, and on the other, greater exploitation of minerals that compensates for the depletion of minerals. The enrichment factor represents a balance between the price of the material and its abundance in the earth’s crust and implies the number of times the species must be concentrated for its extraction to be economically viable. Minerals such as
iron and bauxite have low enrichment factors (around 4), so the specific amount of waste generated per unit of product is relatively low, compared to minerals with higher enrichment factors such as gold and noble metals (over 400) (Spitz and Trudinger 2019). However, the production levels mark the waste volume that the mining industry exhibits.

Figure 3. Production vs ore grade for four different metals. a) Iron, b) copper, c) gold y d) nickel. Area plot: Word mine production, ▲: World average grade, ○: Australian, □: Chilean, ×: South African, and ◊: Canadian grades (Mudd 2009, Giurco et al. 2010, Olafsdottir and Sverdrup 2021, US Geological Survey (USGS) 2021).
It is also relevant to consider that open-pit mines generally produce a more significant amount of mineral residues since the surface attack of the ore requires the removal of soil, overburden, and low-grade ore that is above the deposit. In contrast, underground mines have less waste associated with the mining stage (Lu and Cai 2012). The management strategies for such massive amounts of waste until now have consisted of the disposal and confinement of these large volumes of material, which contrasts with the most desirable alternative, which is to prevent waste before its generation. The inherently extractive nature of the mining industry and limited economic incentives have made it more challenging to achieve waste prevention (Laurence 2011, Bian et al. 2012).

In terms of resources, energy and water are the primary inputs. Several operations are energy-intensive, such as grinding and melting, and its consumption represents not only an environmental issue but also economic conditioning. On the other side, as several of the mineral transformation processes are carried out using water, so its proper management and treatment are crucial issues in arid and semiarid regions.

2.2. Circular economy (CE) in the mineral processing from bibliometric data

The CE involves a set of systemic strategies that allow diverse economic activities to resemble the biogeochemical cycles that govern nature, where residues do not exist, and any product is the raw material or food for another process or system (Ellen MacArthur Foundation 2013). This enables the design of sustainable, integrated systems in which natural resources are preserved and waste is not considered as such but as resources for other uses. It is important to mention that along with its history, CE has acquired elements that are much more than improving resource flows and waste management practices, but also the commitment of society and the design and innovation. There is no consensus on the definition of CE, and there are at least seven comprehensive reviews that address the concept. For example, Kirchherr et al. (2017) reviewed 114 definitions of CE and found that the primary purpose of the CE is considered to be economic prosperity, environmental quality, and social equity. Alhawari et al. (2021) have recently published a compendium of various definitions on CE, and identified that some authors emphasize on recycling, others on eco-efficiency and resource productivity, prolonging the useful life of products, reducing the use of materials, to mentions a few ones. The definition “Circular economy defines its mission as solving the problems from the perspective of reducing the material flux and making the material flow balanced between the ecosystem and the socioeconomic system” (Liu et al. 2009) is close to the approach adopted in this review.

Although the concept of CE was thought up in the mid-1970s (Reike et al. 2018a), the first three papers published with “circular economy” in the title appeared in 2004, and according to the Web of Science database, 1,548 articles have been released from that year to 2020. The three more active Web of Science categories have been environmental sciences, engineering environmental, and green sustainable science and technology. The mining and mineral processing category is in the last quartile, with 13 papers published that include “circular economy” in the title during that period. However, topics related to mining and CE have been covered in other categories as well;
For example, in the last ten years, 54 and 10 papers have been published in the Journal of Cleaner Production including “tailings” and “acid mine drainage” in the title, respectively. The Journal of Cleaner Production is the journal with more publications using “circular economy” in the title.

The CE definition has experienced variations over time, with some authors referring to historical stages as 1.0, 2.0, and 3.0 (Reike et al. 2018a, Calisto Friant et al. 2020). These visions collect different cumulative aspects, which, as new information is generated, are added to establish fundamental principles and a general structure. While CE 1.0 focused on the generation of waste and its safe disposal in dumps, not considering within its analysis the scarcity of resources, CE 3.0 is centered on maximizing the retention of value of a system at times when resource depletion exists (Reike et al. 2018b). From 1970 to 1990, the focus of CE 1.0 was not on waste prevention but on pollution treatment through end-of-pipe technology and the “polluter pays” principle. This was also clearly observed in the mining and mineral processing category, where the publication focus was on purification and detoxification units at the end of gases, liquid, and solid emissions. Examples of these studies were the effect of contamination on the sea (Ellis 1971), the treatment of waste that contains toxic metals such as arsenic (Lee and Rosehart 1972, Laguitton 1976, Oliver, A.J.; Miedema, M.C.; Okuhara, D.N.; Vandergaast 1985), hydrometallurgical processing of waste (Dreisinger 1990), development and improvement of tailing ponds management (Bell 1974), regulations for waste disposal (Peluso 1974, Welch 1985), waste stabilization (Capp et al. 1975), removal of toxic components (SO$_2$) from residual gases (Brown and Brown 1978), dump management (Tassie 1988), design and operation of tailing facilities (Tetu and Pells 1971, Klohn 1972), and waste taxation (Muth 1984). Also, in the case of nuclear and radioactive waste, the management approach was to concentrate and contain (Hunkin 1980, Celeri, J.J.; Lavie, J.M.; Lefebvre, J.; Sousselier 1983). These strategies were novel at that time because the usual approach in the 60’s was to dilute and disperse into the environment or “foul and flee” attitude. Worldwide, the idea of reduce-reuse-recycling obtained notoriety, but this was not observed in the mining and mineral processing sector or was at least absent in the scientific literature.

Later, the CE 2.0, between 1990 and 2010, concentrated on pollution prevention as a way to increase profit through improved process efficiencies and better reputations (Reike et al. 2018a). The integration of preventive and control actions was applied to obtain profits from environmental and business activities. The concepts of industrial ecology, design for the environment, and cleaner production were considered as objective ideas, but they were difficult to implement in mining and mineral processing industries due to their conservative approach in introducing process innovations, and the lack of strict environmental regulations, particularly in developing countries (Hilson 2000).

The more decisive action was the introduction of environmental management systems (EMS) into the industrial operations, particularly by multinational corporations seated in developed countries. These EMS facilitated to fulfill environmental regulations, detect economic and technical benefits, and guarantee that environmental policies were assumed and followed (Hilson, G.; Nayee 2002). Based on Schiffman et al. (1997) and the modification of Hilson and Nayee (2002), the three
essential benefits of implementing EMS in mines are that the personnel are better suited to systematically assess the potential environmental impact in everyday industrial processes, evaluate alternatives, and identify legal requirements and hidden costs. Waste management was the topic more analyzed in the scientific literature in mining and mineral processing in such time period (Figure 4), and it is still today among the most active research topics. However, industrial ecology, cleaner production, and waste management were also analyzed in this period. For example, cleaner production was applied to identify opportunities to reduce the environmental impact and the generation of valuable products from sulfur-containing ultra-fine coals in South Africa (Reddick et al. 2007). Another example is the use of industrial ecology to analyze strategies to reduce the impact of waste from historical sites in Poland and England (Stone 2002, Szczepanski 2003).

Since 2010, the emphasis has been the maximization of value retention as a result of the gained awareness that natural resources cannot be exploited indefinitely, which will be further complicated with forecasted trends in population growth and consumption levels, particularly in underdeveloped countries. Therefore, the CE 3.0 aims to decouple growth from resource extraction through the reduction of natural resources consumption and the encouragement of their recirculation (Corona et al. 2019, Kjaer et al. 2019, Pao and Chen 2019). The mining and mineral processing categories of the Web of Science database reveal the increase of research associated with CE, and at the same time keeping attention to the related concepts of cleaner production, waste management, and waste recycling (Figure 4). However, waste management is still the more scientific active area with three times the level of publication of CE.
From an environmental approach, various industrial practices have been modified as regulations, performance indicators, and technology development. Thus, very reactive actions, such as the direct discharge of effluents and solid residues and the use of bodies with high dilution power (like the ocean), are being superseded by more proactive methods that internalize the concepts of cleaner production and industrial ecology, which focus on waste as new resources. This path from reactive to proactive strategies reflects the route from CE 1.0 to 3.0 (Figure 5). Nevertheless, end-of-pipe technology is still a more common strategy for environmental issues. For example, the session “Material Recycling and Metallurgical Waste Stabilization” of Hydroprocess 2020 focused on arsenic stabilization in tailing (Segura et al. 2020) and arsenic extraction from smelter dust (Parada and Reghezza 2020). Even the presentation with the title in “Circular Economy in Mining” was related to the extraction of valuable elements from the AMD (Zamora et al. 2020). In the same direction, remediation of tailing is still an active area (Stylianou et al. 2020).

It should be noted that preserving resources and reintegrating products and by-products into processes goes beyond the recycling concept. This is how the CE provides a more comprehensive intervention, from design stages to behavioral changes in reducing and reusing materials. To do this, three types of loops associated with circularity can be defined: short, medium-long, and long loops.
Within each loop, there are several alternatives to maximize the value of the products (by-products and waste), incorporating them into the same or different production process, which is known as the retention of value option or ReX. The ReX concept helps to express the nature of the CE and comes from the fact that the various options begin with the prefix “Re” which derives from the Latin “again”, such as Reject, Reuse, Re-adapt, and Recycle (Sihvonen and Ritola 2015). Despite at least 38 distinct ReX words being used in the literature, Reike et al. (2018) summarized them to 10 ReX (Table 1), relating the three types of loops with their ReX-imperatives.

The fundamental difference between the loops is the degree of proximity of the products to the users and their final function. The longer the loop, the system is less efficient and could thus be considered a less desired circularity. However, the longer loops are associated with the flexibility in the use of the recovered material as, for example, only recycling processes generate raw materials that can be used for entirely different purposes than those of the product from where they were obtained (Velázquez-Martínez et al. 2019). Within each loop, there are various methods to retain the value of products (by-products and waste) and incorporate them into the production cycle, which is known as a value retention option. However, it is worth indicating that the CE 3.0 loop emphasis moves to the supply chain, which currently implies closing loops over extensive geographical distances.

Table 1
Loops of Circular Economy 3.0 and their retention value options (ReX) (Reike et al. 2018b). With a shorter loop, the circularity increases, and the flexibility in using the recovered material decrease.

<table>
<thead>
<tr>
<th>Loop</th>
<th>Emphasis</th>
<th>Value retention option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>The product remains close to the user and end-use.</td>
<td>R0: Refuse</td>
<td>Avoid the use of materials.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R1: Reduce</td>
<td>Use less material per unit of product.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R2: Resell/Reuse</td>
<td>Use recycled materials.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R3: Repair</td>
<td>Extend the life of a material.</td>
</tr>
<tr>
<td>Medium-Large</td>
<td>Products are updated, and producers participate again.</td>
<td>R4: Refurbish</td>
<td>Replacement or repair of a part of a multi-component product that results in a general update.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R5: Remanufacture</td>
<td>Reconditioning of the complete structure of a multi-component product.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R6: Repurpose</td>
<td>Use discarded materials with a different function than the original.</td>
</tr>
<tr>
<td>Large</td>
<td>Traditional waste management. Products lose their original function.</td>
<td>R7: Recycle materials</td>
<td>Use materials in any way to avoid the use of new resources.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R8: Recovery of energy</td>
<td>Capture energy contained in waste and integrates it into other processes.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R9: Remine</td>
<td>Recovery of materials after final disposal.</td>
</tr>
</tbody>
</table>
3. R-imperatives in mining and mineral processing.

Mining is an activity that has been traditionally approached from a purely extractive point of view, in which the transformation processes of valuable species are linearly linked with the availability of mineral resources in the deposits. According to several authors, the linear model of relationship with the exploitation of raw materials will no longer be viable in a short-medium term so an accelerated internalization of the CE in the different economic activities will not only reduce immediately the emissions that are generated but also mitigates the uncertainties associated with a paradigm shift in which the shortage of non-renewable raw materials is no longer a determining factor in the growth and development of organizations and societies (Ellen MacArthur Foundation 2013, Lacy and Rutqvist 2015, Sariatli 2017).

Thus, in recent times, the integration of circularity in mining and mineral processing has been conducted through various approaches, including the management of raw materials as water (Figure 6) and waste. In this last point, there are efforts on reducing the amount of waste and reprocessing overburden and tailings for the elimination of environmental hazards and the manufacture of new commercial products (Figure 7) (Guerin 2006, Kinnunen and Kaksonen 2019). The value retention options (ReX) proposed for the CE 3.0 and listed in Table 1 are discussed next, using some cases of application of circularity strategies in mineral processes.

Figure 6. The use of water in mining and mineral processing and the ReX-imperatives
3.1. Refuse (R0)

The concept of “refuse” refers to avoid those processes that generate waste and use significant amounts of raw materials. It may also consider the refusal of the specific reagents’ usage, hazardous chemicals, or critical resources, such as water for mining. Around the world, many mining operations, especially those established in desert areas, have turned into reject the use of freshwater for the beneficiation processes of their minerals in favor of dry processing technologies such as magnetic separation, dense media, and shallow air bed fluidization techniques.

Coal, copper, and iron fine ores have been satisfactorily treated by dry beneficiation (Chalavadi and Singh 2020). For example, in China, dry coal beneficiation becomes an attractive option by using an air dense medium fluidized bed and FGX® separator (Dong et al. 2019). A similar technology was recently studied for copper ores, whose beneficiation consumes large amounts of energy and water. The use of a high-density gas-solid fluidized bed allowed to increase the ore grade about 2% and reduce copper content in tailings to 0.4% (Yan et al. 2019). Examples of other techniques used for different minerals are the separation of chromite grains from ferruginous chromite ore deposits in India using dry high-intensity magnetic separation, the concentration of boron ores and the dry-concentration of tungsten using the gravity Knelson concentrator (Akcil, A.; Akar 2001, Greenwood et al. 2013, Tripathy et al. 2016). A further example in the case of water is the refuse to use continental sources.

In the iron industry, the high-grade hematite rich ores reserves have decreased, and the industry is moving to process lower-grade ore or tailing (Suthers et al. 2019). However, the beneficiation of hematite-goethite ores has significant implications as goethite can generate more fines during
comminution and can carrier for impurities. The concentration of hematite-goethite ores includes wet technologies as spirals, hydrocyclones, and wet magnetic separation (Nunna et al. 2020). Then, the demand for technologies with lower water demand has increased, and research has been carried out for the dry processing of hematite-goethite ores. Thus, dry processing technologies such as dry desliming of iron tailings by air classification (Suthers et al. 2019), dry density-based gravity separation using fluidized bed technology (Oshitani et al. 2013), and thermal roasting followed by magnetic separation (Nunna et al. 2020) has been studied.

In another illustrative example, a critical reagent in copper production is sulfuric acid, which is used in leaching processing. Recent studies show that it is possible to partially refuse the consumption of fresh acid in the curing and leaching stages by using weak solutions obtained in the gas treatment of copper smelting process (Araya, Toro, et al. 2020).

3.2. Reduce (R1)

One of the short-loop options that have the most significant impact on the sustainability of mining processes is mainly related to the consumption decrease of critical inputs for mineral processing, such as water and energy. It may also include efforts to reduce waste production, such as the anthropogenic emission of $\text{SO}_2$, tailings, and rock waste. The reduction in the consumption of resources and the generation of waste are closely linked to the efficiency of the processes, where the operational and technological development factors are dynamic and influential.

The mining industry's interactions with water resources are deeply complex but implementing practices and strategies that promote sustainable water management can have significant economic and environmental profits. Sometimes, the industries have a strong interaction with neighboring communities, even competing for water use. Therefore, water management improvements can provide important social benefits. For these purposes, it is essential to have an assessment that accurately records the water consumption at all stages of a mining's life.

Water footprint methods have been developed significantly in the last decade and have recently been aligned with life cycle assessment approaches. Despite these advances, relatively few studies have focused on applying these methods in the mining and mineral processing industries (Chan et al. 2014, Northey et al. 2016, 2019). Some limitations were pointed by Northey et al. (2016) that hinder the ability to carry out this type of study, including the availability of data on water use at the mine site, inventory data for mining supply chains, the uncertainty of post-closure impacts, and the difficulty of accounting for cumulative impacts and extreme events (for example, dam failures).

Standardized assessment of the water use impacts associated with mining and mineral processing will allow for more fair and meaningful comparisons with other industrial sectors such as agriculture and manufacturing. The water footprint methodology can also help to develop a benchmarking scheme for water efficiency in mineral processing operations. For example, Northey et al. (2019) compiled 8,314 water-related data points from 359 mining company. Initial data
analysis reveals considerable variability in water withdrawals, use efficiency, and discharges between mining operations.

The Chilean copper mining experience is a good example to analyze the water management of this industry in a 'Reduce' approach, due to the most operations are in places where water is scarce. This ReX has been handled by two ways: the increase of the efficiency in the water usage and the substitution of fresh water by seawater.

In recent years, the specific water consumption has decreased significantly for the concentration of minerals, reaching in 2017 a unit coefficient of 0.45 m³/t. This effort has had a relevant impact in the industry since this type of processing consumes the greatest amount of water in mining (four times more than hydrometallurgical processes). On the other hand, the water usage in hydrometallurgical processes is close to the critical unit consumption, around 0.1 m³/t (Figure 8a), which explains that no significant variations have reached in recent years. Additionally, operations have aimed to decrease their water footprint, through the intensive recirculation of processing water. Recycling rates of about 75.7% and 70% were estimated for the concentrator and hydrometallurgical plants, respectively (COCHILCO 2018).

In the other approach, it is expected that the amount of water required for mining operations will increase even further with the forecasted decrease in ore grades and increased demand for metals. Thus, several industries have been forced to seek non-traditional sources of water. In this context, seawater has gradually gained relevance as an alternative source to meet the industrial requirements, both raw seawater and desalinated are becoming increasingly important in Chile due to the proximity of industrial areas to the coastline and the unconstrained seawater supply (Cisternas and Gálvez 2017, Northey et al. 2017). Nevertheless, mining plants are frequently at high altitudes, which on one side, supposes a paradigm between the abundant source of seawater and the high transportation costs by pumping, and the other, explains the current position of the seawater use on the total mining water consumption (Figure 8b) (COCHILCO 2018).
The high capital and operating costs required for the use of seawater have limited the uptake to cases where there is not a real alternative, and the risk of a water supply deficit is extremely costly. A lower-cost option is either the use of raw seawater or partially treated seawater. Raw seawater is generally unsuitable for many processes, particularly flotation, although in some cases where pyrite content is below 3%, raw seawater can be used without affecting copper recovery rates (Castro 2018, Cruz et al. 2021).

Figure 9 shows the water production cost for the use of raw and desalinated seawater at different levels of elevations. Water transportation can be important in energy consumption and water cost (Araya et al. 2017, Herrera-León et al. 2019). Also, the increased use of desalination and desalinated water transportation will generate indirect environmental impacts through increased demand for electricity. Thereby, for the case of Chile, the electricity grid that supplies northern and central regions depends heavily on fossil fuels (41.2% coal and 16.5% natural gas), despite the significant investments in renewable energy in recent years (Vyhmeister et al. 2017, Moreno-Leiva et al. 2020, Pollack et al. 2020). The increased demand for electricity will lead to increased atmospheric emissions that will affect air quality and contribute to climate change. This has led to the fact that in areas with remote access to water, it is strictly necessary to advance in closing the water loops (Kinnunen et al. 2021). It is increasingly common to find industrial operations that also use seawater directly in the processing of other minerals around the world, such as zinc, uranium, and iodine, either by hydrometallurgical or by concentration processes (Dreisinger et al. 2008, Ordóñez et al. 2013).
Among the different unit operations that mineral processing has, crushing is a key step and represents a relevant energy consumption, between 30 and 50% of the total energy of the process (Wills and Napier-Munn 2006). Therefore, since the last decades, research has been done on opportunities to increase energy efficiency in milling processes as part of efforts to reduce energy use. This search has been approached from the point of view of the design of new grinding technologies, the control of existing operations and the optimization of the circuits, including the integration of renewable energy sources (Giurco et al. 2014, Ortiz et al. 2020).

In milling operations, semi-autogenous technology (SAG) is the most frequently used, however, multiple studies have proposed new developments that achieve greater efficiency, such as high pressure grinding (HPGR). This technology was originally designed in the 1980s for the cement and diamond industry (Morley 2006), and ten years later, it was incorporated for iron ores. The advantages in its reduction mechanism, based on the generation of fractures from a confined bed, allowed this technology to be adopted in concentrating plants for hard copper and gold minerals, where the energy requirements resulted lower than for SAG (Pamparana and Klein 2021). Davaanyam et al. (2015) determined that the use of HPGR could translate in a cost reduction of energetics between 11-32% compared with SAG.

Many mining operations are in areas where solar availability is high. For these cases, the evaluation of the integration of photovoltaic power generation systems in comminution processes arouses interest, especially in recent times. Thus, for example, Ortiz et al. (2020) determined that the use of a photovoltaic system with battery energy storage (PV-BESS) has the potential to reduce total energy costs by 27%. In the case of gold production in China, given the extension of its territory and the predominance of its production in the world, the importance of the energy supply network considering the renewable sources that each locality has (Chen et al. 2018). In addition to the reduce approach performed on the use of strategical resources (water and energy), it is extended...
to the handling of waste flows. Thus, treatment steps that minimize the volume of tailings, rock waste and slags have been gradually incorporated.

In the case of tailings, the programs to reduce the quantity of disposed material are frequently related to water recovery, since the best method to decrease the water supply cost is reducing demand of fresh water. Consequently, gravity thickening unit operations acquire a crucial role within operating flowsheets. It is within the tailings circuit where the highest amount of water is recovered and returned to the process. Solid-liquid separation by gravity sedimentation is enhanced by aggregating fine particles within dilute tailings feed suspensions, forming beds within the thickener from which a concentrated underflow solid suspension can be collected (Quezada et al. 2020). At the same time, clarified liquor is recovered at the peripheral overflow. For example, Centinela Mine (Antofagasta Minerals Group, Chile) incorporated paste thickened tailings with seawater on an industrial scale, allowing for greater efficiency and a lower risk of infiltration in the subsoil layers. The paste tailings constitute a thickening product with which it is sought to eliminate the water from the slurries until the particles are not segregated. The water is extracted to transform that mixture into a similar paste that may reach over 65% of solids. The consequences of implementing this strategy have been significant for the industry, where they have steadily increased the recovery of water from the tailings. Figure 10 shows the evolution of the global solid percentages of Centinela Mine during the 2014-2018 period, highlighting the time when three paste thickeners were incorporated in 2015.

![Figure 10. Evolution of global solid percentages of thickened tailings of Centinela Mine, in the 2014-2018 period (Source Centinela Mine).](image)

In other mining countries as China, the occupied land areas and dam collapsing are challenges related to the massive quantity of waste generated; it is estimated that China produces about 600
million tons per year of tailings (Lu et al. 2018). On one side, it is necessary to decrease the volume of tailings and, on the other side, reduce the amount of water associated with that waste. Paste thickening has become a promising technology for addressing this environmental and operational issues offering environmental, technical, and economic benefits (Yin et al. 2020). Several cases have reached thickened tailings with 69-76% solids. In a similar approach to copper operation, the coal industry has developed solid-liquid separation by dewatering fine coal tailings. The technologies applied for dewatering are vibrating basket centrifuges, scroll-type centrifuges, screen bowl centrifuges, and solid bowl centrifuges as well as belt-press filters, high-pressure disk filters, and membrane filter presses, some of which are used since many years (Lockhart and Veal 1996, Nguyen et al. 2021). Also, studies on the dewatering circuit can improve the efficiency of the process (Gálvez et al. 2014, Tripathy et al. 2021).

Although the extraction of water from tailings is the primary way to reduce the water footprint, it is necessary to consider the close relationship between the thickened pulp's density and the energy consumption involved in its pumping, from the thickeners to the tailing storage facilities. Here comes the importance of the rheological properties of slurries since their pumping could incur in excessive energy costs (Boger 2013, Jeldres and Jeldres 2020). Commonly, concentrated tailings exhibit non-Newtonian behavior. They have rather an elastic limit, known as the yield stress, which represents the critical shear stress that must be overcome before the pulp can flow. The relationship between the pulp's density and the elastic limit follows an exponential law where small changes in the percentage of solids lead to a significant increase in pumping energy requirements. A schematic representation of the implications of thickening technology on tailings' density and rheological behavior is shown in Figure 11. When the underflow thickens to a high concentration, the energy cost per pump can reach unviable values. In such cases, operators may be required to dilute again the thickened tailings, which means sacrificing water that could have been recirculated for upstream operations. However, the definition of the appropriate strategy to close the water circuit depends on each industry, and mining companies located in areas of water scarcity must maximize recirculation. Ihle and Kracht (2018) stated that the production of thickened tailings and the corresponding recovery of more water could be more energy-efficient than conventional tailings when there is a remote water supply. In such case, the authors exemplified their study considering the use of seawater.
Interestingly, works have analyzed in detail the relationship between water consumption and energy requirements in tailings management (Gunson et al. 2010, Ihle 2013, Nguyen et al. 2014). Adiansyah et al. (2016) analyzed five different tailings disposal strategies, presenting an optimal scheme in terms of water saving, water management, and energy consumption. The authors indicated different initiatives that Chilean and Australian mining industries have taken to reduce water and energy consumption. As water scarcity increases, the energy required to supply a unit of water to a mine site grows as well. Sahoo et al. (2014) proposed a model to estimate water and energy requirements for water pumping in opencast mines and analyze the variations with the depth as mining progresses. More recently, an analysis of the influence of energy consumption in water treatment systems and its impact on the environment, considering water quality requirements, water distribution systems, and how different energy combination setups affect these variables was published (Ramírez et al. 2019). It was concluded that the selection of energy sources, changing water desalination process, optimizing water intake, choosing water reuse, and using untreated seawater in industrial processes are the more important measures to reduce the environmental impact.

Another technology used to recover water from the tailings is through filtration. The main advantage is their ability to produce cakes with a residual humidity between 15% and 22%, with the consequently high recovery of water. The presence of clays mainly affects the filtration rate and the productivity of the filters but, independently of their content, it is possible to achieve an efficient water recovery. Another aspect associated with tailings filtration technology is the
generation of deposits more physically stable. The future of global mining should point in the
direction of filtered tailings for various reasons such as the geotechnical safety of the deposit,
lower operating costs, faster times for claiming the deposit, and for optimizing water recovery,
which impacts very positively in the rational use of water resources.

The control of dust in mining areas frequently uses water; another way to reduce water
consumption is to apply a more efficient way for dust depressing. Gunson et al. (2012) found that
road dust suppression was significant water-consuming processes, accounting for about 9% of
total water use, and concluded that an optimal road dust suppression method was the use of a
dust binder on the road network. A natural product available worldwide used for dust suppression
that can reduce water consumption is Bischofite (MgCl₂·6H₂O), normally obtained from salt flats
or salty lakes in either solid or diluted form (Jones and Surdahl 2014). In this context, Gonzalez et
al. (2019) indicated that water consumption in one year for the irrigation of haul roads in an open-
pit mine is on average 153 times higher than the water required for roads treated with Bischofite.

As mentioned before, the incorporation of dry technologies goes directly to reduce the process
water consumption. In the coal industry, 66% of mines are in arid areas, which motivates the
development of dry beneficiation, resulting in a low-cost separation and free of pollution. The use
of gas-solid fluidized beds and gravity-based processes are the most frequent techniques such as
air dense medium fluidized bed (ADMFB) and FGX separator (Dong et al. 2019, Luo et al. 2019, Xu
et al. 2019).

3.3. Reuse (R2)

Reuse is another short-loop strategy that has a place in the management of mineral concentration
processes. Reuse is usually applied to a second consumer of a product or material with almost no
modification and works similar to new products or materials (Bakker et al. 2014). One example in
mineral processing, associated with the R2 value retention option, is the use of tailings in other
applications. Mining tailings are a suspension of residual mineral in water that, thanks to its small
particle size, has been studied for reuse as a partial or total substitute in cement manufacturing.

It is interesting to visualize options of this type, given that tailings are mainly considered as waste,
but have the potential to positively intervene in the circularity of the cement industry by
promoting the reduction of virgin resource consumption such as limestone, bauxite, clay, sand,
and gypsum (Wang, Yao, et al. 2019). Cement production is an activity considered as one of the
three industrial processes that have the highest environmental impact, together with the use of
fossil fuels and the exploitation of land (Andrew 2018). The volume of material used in the
production of concrete is only second to water consumption by mass and directly accounts for 7-
8% of global anthropogenic CO₂ emissions (Scrivener et al. 2018, Miller and Myers 2020). For this
reason, in 2017, UNESCO called researchers from around the world to join forces to reduce CO₂
emissions from the cement industry and improve its efficiency and sustainability (Editorial 2018).

One of the studies that are being carried out by research centers in this area is related to the use
of tailings from various mineral processes as a raw material for manufacturing concrete. In Chile,
the use of copper tailings as construction materials has been studied, significantly improving the performance of cement materials. In one of such projects, the engineering faculty of the Pontifical Catholic University of Chile in conjunction with the company Minera San Pedro, have analyzed the technical feasibility of creating structural concrete through the use of mining tailings in cement replacement. After the optimization of some operational conditions such as the temperature and the time of demolition, a replacement rate of up to 40% has been reached, which is a notable fraction, compared to various studies in which replacement ratios between 5- 30% are reported (Onuaguluchi and Eren 2012, 2013, Esmaeili and Aslani 2019). However, in other studies, it has been observed that copper tailings may be utilized for the partial replacement of natural fine aggregates up to a 60% (Thomas et al. 2013).

Furthermore, gold mill tailings have been studied for the elaboration of construction bricks (Roy et al. 2007). Additives, such as Portland cement and black cotton soils, were mixed with the mill tailings because the tailing alone did not give the desired results. It was found that mixtures containing 20% of cement met the required properties. In the same direction, the use of iron tailings in construction (Zhang et al. 2006) and to replace clays in the production of fired bricks had been studied with reports of good structural performance (Chen et al. 2011, Yang et al. 2014).

Although the study of tailing reuse is valuable, it is far from being a short-term solution for the produced tailings in many locations around the world, e.g., even if the entire annual production of concrete could be made with tailings in Chile, less than 10% of the tailings generated each year would be used. In addition, other important challenge to analyze is the transport logistic, due to tailing facilities are normally distant from cement plants, so the cost associated to put tailings available become an important item. In an environmental point-of-view, the emissions related to transportation may compensate the reduction of cement production by the usual raw materials.

From a different perspective, the ReX reuse also has been addressed through the recovery of wastewater, which is subsequently related to reducing process-water consumption. The search for cost-effective methods to reduce water consumption is considered an important challenge for the sustainability of the flotation process. Lin et al. (2020) evaluated the feasibility to reuse process water in certain stages of the molybdenite and bismuthinite flotation circuit at two levels: lab and industrial scale. In the studies at the laboratory scale, the recycled water affected the flotation performance of molybdenite and bismuthinite mainly due to the increase in the residual content of reagents until reaching saturation. In the subsequent industrial-scale test, the reagent dosage was adjusted, and the reuse of water proved to be feasible for the production of concentrate. The reuse of internal process water has a significant impact on the operation, not only through the saving of around 600 t/y of fresh water but also by reducing the reagent dose required in flotation. The reuse of water in the flotation circuit opens spaces for more studies and applications on an industrial scale, given promising results from an economic and ecological point of view.
3.4. Repair (R3), Refurbish (R4), and Remanufacture (R5)

These ReX-imperatives are seldom used in the context of mining and mineral processing activities. Of course, industries as customers use several products, such as reagents and equipment, where these ReX-imperatives can be applied; however, these are not the core mining activities. The purpose of repair is to extend the lifetime of the product, and therefore can be applied to equipment and tools used in mining and mineral processing. Refurbish and remanufacture are concepts with a similar application in mining activities. Both ReXs are related to replace, repair, check, clean and/or upgrade equipment, activities traditionally carried out as part of the routine maintenance work. In an industrial approach, remanufacture looks for turning used products into new ones with the same quality and functionality as new ones. For more information on these types of ReX, the reader is referred to Sihvonen and Ritola (2015).

In any production process, such as metallurgy, various equipment is used, such as pumps, filters, centrifuges, tanks, etc. Maintenance units are an essential part of the work carried out in mining companies, which seek from an operational efficiency perspective to prolong the life cycle of the equipment involved in the operation. In fact, in the literature, the most recurrent activities in the search for the extension of the equipment life cycle are the predictive and preventive maintenances (Fontana et al. 2021). However, new concepts have emerged that have highlighted the importance of design in different fields related to CE, such as durability/reliability, modularity, and part standardization, ease of maintenance and repair, upgradability, and disassembly and reassembly. Equipment supplier companies should pay special attention to the development of these design tools, which will impact mineral processes, due to about 60% of the operating cost in mining companies is related to the purchase of goods and services from providers (Fundación Chile 2014).

In the same way, other materials such as plastics and tires, which are of intensive use in mining, have gradually acquired a greater position with respect to the ReX of remanufacturing, repair and refurbish (Campbell-Johnston et al. 2020, Markl and Lackner 2020, Sherwood 2020). In the open-pit coal exploitation, it is estimated that 12% of the cost is occupied by the tires, being among the main expenditures for this type of ore mining (Kvasova et al. 2017).

3.5. Repurpose (R6)

Repurposing is a concept frequently used by the industrial design and craft culture; however, it can also be considered an option for mining and mineral processing industries. The concept of “repurpose” is related with the idea of reusing unwanted materials for another function, providing a new life to such material. One example that has received considerable interest is the use of mining waste for CO₂ sequestration using mineral carbonation (Li et al. 2018, Marín et al. 2021). In mineral carbonation, the CO₂ reacts with oxides, hydroxides, or silicates of calcium, magnesium, and iron to produce geologically stable carbonate species and silica. The impact of this technology on CO₂ footprint reduction of mineral operation can be important. For example, it was determined that the tailings of the Dumont Nickel Project of RNC Minerals could capture about 16% of the
CO₂ annually emitted by their planned mining operation (Gras et al. 2020). Although this technology is not yet economically competitive, new studies are helping to reduce its costs, energy use, and environmental impact (Hamilton et al. 2020). Another element to highlight is the possibility to give value to the by-products.

The valorization of tailings within the mineral carbonation can be considered in the recovery of valuable species before carbonation and the potential use of carbonation products (Li et al. 2018, Azadi et al. 2019). The carbonation products can be classified as either high volume, but low technology or low volume, but high technology. The valorization can be of different natures and depends on the available tailings and the mineral processing routes and the carbonation process itself (Azdarpour et al. 2015).

Examples of recovery of metals or other valuable species in an integrated way with carbonation process are the recovery of iron oxide and amorphous silica along with the production of a carbonate product from serpentine rocks of a nickel mine (Teir et al. 2007). The process includes the use of hydrochloric acid or nitric acid and sodium hydroxide to change the pH conditions in the process. The process requires such quantities of NaOH that make the application of the process difficult from an economic point of view and does not consider the recovery of nickel. For nickel recovery, prior to carbonation, it has been proposed to use sulfuric acid to disintegrate chrysotile (serpentine-kaolinite) and recover nickel by flotation, while tailings, rich in MgO, have been considered a candidate to capture and sequester CO₂ (Uddin et al. 2012). On the other hand, microwave pretreatment has improved nickel recovery and the carbonation process by converting serpentine into olivine (Bobicki et al. 2014). From this point of view, there is a wide gap in the integration of valuable species recovery and the carbonation process. This situation is not surprising because the recovery of valuable species from tailings, without integration, is still in a nascent stage.

The products of high-volume, low-technology carbonation include the production of construction materials, aggregates, and cementitious phases (Kusin et al. 2020). The possibility of using tailings carbonation products as a partial substitute for cement in the preparation of concrete bricks is an option to help reduce the adverse effects of construction material production and tailings deposits, along with reducing the effects of carbon dioxide. For example, carbonated kimberlite tailings have been studied for cement replacement between 10% and 20% (Chakravarthy et al. 2020). The results obtained confirm the possibility of using carbonated kimberlite to replace the cement partially. Such study demonstrated the potential use of mining tailings to prototype CO₂ capture in sustainable building materials to positively impact the growing demand for cement-based products. In addition to these types of applications, the use of carbonation products has been considered in the stability of mining tailings and in the control of AMD (Azadi et al. 2019).

High-tech, low-volume products correspond to potential high-purity materials with well-defined particle sizes and morphologies, such as nanoparticles of uniform composition, size, and shape. This requires processes where cations can be extracted and thus be able to control their characteristics (Sanna et al. 2014). Its applications are diverse, including catalysts,
chromatography, ceramics, electronics, pigments, pharmacy, among others. For example, the products of carbonation can be used to produce high purity amorphous silicon or calcium carbonate. This demands adequate specifications according to their intended application, thus, for example, the six different forms in which calcium carbonate precipitates can find different applications depending on its crystalline forms, purity, physical-chemical properties, etc. (Li et al. 2013).

Another example of repurposing is the use of the reject brine of desalination process in mineral processing. Studies have shown that the leaching of caliche using reject brine is technically feasible and delivers similar results than using seawater (Ordóñez et al. 2015, 2017). In another study, the use of reject brine in the leaching of pure chalcocite provides better results than the use of seawater (Torres et al. 2020).

### 3.6. Recycle materials (R7)

Recycling, which is one of the more popular ReX, is the process of transforming waste materials into new materials. The objective is to prevent the consumption of freshly mining materials and resources (Ghisellini et al. 2016). Recycling has become a topic of increasing and transversal use for various productive activities. However, at present, its application in mineral processes is still limited.

It should be noted that the focus of this work is related to the CE strategies applied to mineral processes, so it does not consider, for example, the extensive information available on recycling of end-of-life products, e.g., electronic scrap (Kaya 2016, Zhang and Xu 2016, Abdelbasir et al. 2018, Katiyar and Randhawa 2020, Mansur et al. 2021). However, as was indicated in the introduction, the implementation of CE, including metal recycling, will reduce the global material extraction by about 10%, including a decrease of about 27% in metal extractions (Wiebe et al. 2019).

### 3.7. Recovery of energy (R8)

This concept is usually used as capturing energy embodied in waste or the use of biomass (Mayer et al. 2019, Mukherjee et al. 2020). In industrial processes, including mining, this concept is related to energy integration, where the excess energy (typically in the form of heat) from some operations is recovered and used within another operation or stage. For example, in the iron and steel industry, which is the second largest energy user in the global industrial sectors, the blast furnace slag can be used for in-situ fixation of CO₂ using the waste heat by the integration of the carbonation process and the process energy (Gao et al. 2019). In the same way, when the blast furnace is operating, it simultaneously converts the higher pressure in electricity (Sun et al. 2020).

An important contribution in the field of metallurgy was the development of the flash smelting process for smelting sulfide concentrates. Low energy consumption was achieved by utilizing the latent reaction heat of the concentrate for smelting. Also, polluting emissions were reduced by the production of sulfuric acid and the heat recovery from waste gases from the plant. This was
possible by oxygen enrichment of the process air and the control of fuel oil throughput required for optimal operation (Koskinen and Torvela 1989). The notion of the generation of energy from waste generated by sub-activities in the mining and mineral processing industry can also be considered, for example, the energy production from waste tire (Sathiskumar and Karthikeyan 2019). However, again, this is not the core activity of this industrial sector.

3.8. Re-mine (R9)

One of the most widely used ReX by the mining industry is remine, mainly because the extractive nature of this economic activity involves the generation and dumping of large amounts of waste, which generally contain potentially recoverable species of growing commercial interest. Remine is defined as the recovery of raw materials from dumped waste. In mining, as mentioned before, the main mineral residues produced are overburden, waste rock, leached ores, tailings, and slags. One aspect that has undoubtedly led to the application of CE in mining, particularly in the form of remining, is the increasing demand for strategic metals whose supply is uncertain.

Performing an analysis of the technologies involved in the valorization of noble, base, and strategic metals from mining waste (tailings, slags and waste rock) it can be seen that, historically, the largest number of reported treatments refers to the most traditional hydrometallurgical and pyrometallurgical processes for base metals such as copper (253 and 412, respectively) and some strategic metals that are frequently found in residual minerals as cobalt and vanadium (Table 2). The number of reports associated with precious and rare earth metals is still low. However, as can also be observed in Table 2, the number of recent scientific articles by technology (since 2019) focuses on the valorization of Rare Earth Elements (REEs), with emphasis on biotechnological processes such as bioleaching and dry beneficiation processes. This reflects the growing interest to develop more environmentally friendly technologies. In the literature survey on this topic, concepts as e-waste and electronic scrap were not considered.
Table 2.

Leading technologies for the valorization of several metals from mine waste. Left table shows the historical publications since 1975, and the color intensity denotes the number of publications. The right table shows the relationship between new publications (since 2019) and total, where darker cells indicate trending topics. LX: leaching, BL: bioleaching, SX: solvent extraction, SM: smelting and refining, DB: dry beneficiation and FL: flotation.

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Color scale

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One of the ways to implement a cleaner production strategy is the extractive treatment of commercially attractive elements remaining in the waste effluents and massive waste. The extraction of valuable species from mining waste must first be evaluated to determine if reprocessing does not imply a more significant impact than the simple disposal, stabilization, or confinement. Under certain conditions, extractive management may carry greater environmental risks than keeping them in their current state (Edraki et al. 2014).

In the case of tailings, it has been shown that its solid matrix can still contain valuable metals, representing a potential source of raw materials that could be reprocessed after due evaluation and availability of suitable technology (Alcalde et al. 2018). Feasibility analysis should weigh the concentrations of metals and impurities, the market price of metals, and the quantification of resources (Nuss and Blengini 2018, Kinnunen and Kaksonen 2019). In the quantification and qualification of tailings deposits, Chile has advanced through the cadaster and characterization of mining tailings deposits distributed throughout the territory, which has been developed in increasing stages by the National Geology and Mining Service (SERNAGEOMIN) (SERNAGEOMIN 2016). Some of the tailing deposits may have a relatively high content of valuable metals as REEs, Platinum-group metals (PGMs), and base metals (Figure 12). The main advantages that drive the extractive treatment of tailings are the lower cost of processing compared to the operation of a new mine, conservation of resources that ensure the sustainability of the industry, and the management of sources of pollution to the environment (Antonijević et al. 2008).
Figure 12. Geochemical data of tailings deposits in Chile. Data corresponding to the average of 585 deposits (SERNAGEOMIN 2020). PPC corresponds to compounds lost by calcination such as carbonates.

The recovery of valuable components from tailings is a field that is still in early stages around the world. However, a substantial development is projected in the medium-long term, to the extent that greater knowledge and characterization of waste is handled. The transformation from a linear economy to a circular one requires addressing challenges that are beyond the scope of mining operations, such as the establishment of new closed-loop value chains, in which various stakeholders will need to be involved.

Applying the approach of CE 3.0, through the option of retention of value R9: Remine, there are some notable initiatives, although mostly are in the stage of experimental study and evaluation. As these studies develop and allow us to understand, control, and scale-up the results, they will face the challenge of incorporating major productive sectors.

The Chilean mining industry, protagonist of the world copper activity, has some experience in remining issues; some of which have been carried out for decades, however under an unsystematic approach, such as the case of copper recovery from tailings gutters in the Chuquicamata and El Salvador mines, in the mid-20th century. Among other more recent initiatives are the reprocessing of tailings produced by the El Teniente mine by Minera Valle Central, which is carried out with high standards of efficiency, the retreatment of tailings produced by Minera Candelaria by the Compañía de Aceros del Pacífico. Since 2005 the company EcoMetales, a subsidiary of Codelco Technologies Ltd., has been treating foundry dusts and refining effluents for extractive purposes to recover valuable metal species. Regarding the reprocessing of leaching debris, this has been an activity carried out in situ by several mining companies, as part of their strategies for better use of resources.
It is important to point out that currently, the economic contribution of secondary metal production in Chile is still a minority, compared to the contributions of primary mining. Indeed, secondary copper mining is estimated to have an impact equivalent to just 1% of mine production. It is expected that, in the future, as new circularity strategies are incorporated, this fraction will increase. In other countries with a mining tradition, such as South Africa and China, the introduction of CE has led to the contribution of secondary copper production rising up to 30% of their total mining activity (Dong et al. 2020).

In Chile, the Ministry of Mining is promoting a National Tailings Policy that covers the safe management, monitoring, traceability, and control of tailings deposits. Within this framework, the remediation of inactive sites has been promoted, and the reprocessing of deposits has been encouraged. In the same way, the Corporation for the Promotion of Production of Chile (CORFO) has created instruments of the Strategic Technological Programs that face the recovery of elements of value (CESCO 2020). Among the different initiatives that are being developed to exploit value from tailings, is a project led by CODELCO, a state-owned copper producer, who, through its subsidiary CodelcoTech, has identified and quantified the elements that have the potential to be exploited from secondary sources, including some strategic species such as REEs.

Only few works address the issue of mining tailings valorization from a techno-economic analysis approach. Araya et al. (2020b) determined the economic indicators for Rare Earth Oxides (REOs) and V₂O₅ production projects. The results indicate that the benefit of REOs is marginal, still being risky, while for V₂O₅ the return is positive after 14 years. The variables that mainly determine the viability of this type of projects are the price of these products and their discount rate. Considering that Vanadium is the main CRMs found in the studied tailings, it was concluded that valorizing inactive tailings might be a feasible option to ensure profitable use of mine wastes and to diversify CRMs supply. Recently Araya et al. (2021) presented a framework, based on real options analysis and sensitivity and uncertainty analysis, to assess the economic risk related to the re-processing of mine tailings to produce critical materials.

From a biotechnological approach, through an early experimental study, the use of biomass from Pseudomonas stutzeri (bacterium) and Gracilaria chilensis (algae) have been investigated for the selective recovery of copper from abandoned tailings by biosorption, and for the biosynthesis of copper nanoparticles, taking advantage of the natural content polysaccharides on the cell walls of marine algae (brown and red algae) and bacteria. These biopolymers have a reported ability not only to adsorb metals but also to reduce them (Castro et al. 2013, Ordóñez and Wong 2019, Cortés et al. 2020). The most abundant functional groups related to the metal-biomass interaction are carboxyl, amino, phosphate, hydroxyl, sulfhydryl and sulfonate ones (Volesky 2007). The results of the study showed that copper nanoparticles are in the reduced form and have a spherical shape of about 80 nm in diameter (Figure 13). Another important observation made is that biosynthesis occurred extracellularly for both biomasses, demonstrating that the involved mechanisms used for these biomasses are independent of metabolism, which indicates that the process does not require to keep the cells alive (Ordóñez and Wong 2019).
Figure 13. Biosynthesized copper nanoparticles by *Pseudomonas stutzeri*. a) Microphotograph of spherical nanoparticles and b) EDX analysis confirms the presence of copper (Ordóñez and Wong 2019).

Conventional methods for synthesizing nanoparticles involve the use of reducing agents, chemicals (organic solvents), high energy consumption due to ultramoulding and non-biodegradable stabilizing agents, making their synthesis an expensive and polluting process (Castro *et al.* 2013). However, metal nanoparticles have great scientific and technological interest because they have unique optoelectric and physicochemical properties, due to their crystallographic and morphological characteristics. The use of nanoparticles is playing an increasingly important role in the development of new key technologies applied to electronics, catalysis, drug release, cancer therapy, gas detection, antibacterial agent, and monitoring (Mack *et al.* 2007, Castro *et al.* 2013).

Although the recovery of metal nanoparticles by biotechnological methods have been increasingly described for microorganisms and marine algae, the biosynthesis from mine or industrial wastes, recently termed as “Bio-nano-mining” is an emergent discipline that requires several stages of maturation, but that has demonstrated to be feasible and a cleaner, cost-effective and efficient way to obtain high-value materials nanomaterials (Wong-Pinto *et al.* 2020).

The scientific activity associated with the remining of mineral waste has been largely based on studies on the treatment of tailings and slags. In fact, the recovery of species from slags has almost 400 studies published in the scientific literature, which is much higher than the 51 articles referring to tailings. However, if the analysis of publications is performed for the last two years only an opposite trend is identified. Research works focusing on remining of tailings represent 58% of the depository, while slags only 35%. The first efforts on the slags reprocessing date from 2001, and for tailings, 10 years later. The environmental aspects related to the smelting operation, such as the releasing of arsenic and heavy metals to air as particulate matter, have been additional drivers for its intensive study.
The copper smelting dust has been used as a source of economic and environmentally valuable species particularly when treated with hydrometallurgical processes, which involve acid leaching, cementation, and precipitation. Reportedly, this approach does not present high energy demands and does not produce secondary pollution. When waste acid produced during washing of sulfur dioxide flue gas, is used for leaching of the dust, the recovery of valuable metals is done from the dust and the waste acid simultaneously (Xu et al. 2020). In a similar approach, elements such as Niobium and Titanium have been obtained with recoveries greater than 90% using a pyro-hydrometallurgy technique from an electric arc furnace slag (Kim and Azimi 2020).

4. Conclusions

The application of the CE to metal extractive processes can be in its early stages. Although there are important efforts to reduce environmental impacts, most efforts are still in end-of-pipe technologies, a strategy closer to EC 1.0. Thus, it is common to find proposals such as tailings treatment to eliminate pollutants, gas treatment to reduce the presence of toxic elements, or improvements in water recovery.

The more important actions in short loops correspond to the reduction of water consumption using technologies that demand less process water or that are engineered to minimize water losses. Also, the use of seawater to reduce the consumption of continental water in arid zones has become an increasingly important practice. Another action in the short loop categories is the potential use of mining wastes as construction materials; however, its impact in the grand scheme is limited when the massive amount of waste is compared with the volume of material required in construction. At medium-large loops, the concept of repurpose has been analyzed to use mining waste for CO₂ sequestration using carbonation, a technology that has not been applied yet but presents promising advances. Carbonation can also produce material that can be used in construction or high-tech byproduct. In the large loops, remine of mining waste is the more valuable action, that is usually denominated waste valorization. Several studies search for the recovery of high values materials from waste such as critical material and nanoparticles from tailing.

The main challenges for the mining industry remain in the generation of large quantities of tailings and the vast use of energy and water resources. Thus, major changes are required to replace current technology with alternatives that offer a significant reduction in resource consumption. Process designs should change to consider the separation of contaminant and valuable species within the process and not as end-of-pipe technology. This would allow it to be more aligned with the CE concept and could bring positive effects from an economic and environmental point of view.

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