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Conclusion

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Critical raw materials (CRMs) are crucial materials for the economy. Reliable and unhindered access to CRMs is important for various industrial applications, modern technologies, and green, or clean, energy technologies, including solar panels, wind turbines, and electric vehicles (Dias et al., 2020; European Commission, 2020). Europe has limited access to primary CRM-containing resources. Alternative sources of these materials have to be considered one of the major steps toward ensuring their steady and secure supply. The residues generated during mining, mineral processing, and metallurgical activities can host significant amounts of CRMs and can be regarded as their promising secondary resource. These residues are often stockpiled or stored in dams putting strain on the surrounding environment and occupying large land surfaces. Therefore recovering CRMs from mining residues can contribute to economic revalorization and environmental rehabilitation.

The advantages of industrial residue reprocessing include:

- reducing the environmental risks,
- economic and political interest related to the extraction of critical materials (e.g., reducing raw materials' dependency on other countries),
- higher efficiency of resource utilization,
- creation of new jobs, and
- technological development and advancement encouraged by the demand for innovative approaches for residue reprocessing.

Despite these advantages, combined with attractive concentrations and largely available tonnages of some industrial residues, the extraction of CRMs from them presents significant challenges (e.g., environmental, economic, and technological). This book addressed these challenges in the separate chapters.

Chapter 1 was dedicated to introducing the CRM-containing residues, their properties, and differences. Being generated at the different stages of the natural resource extraction and processing, these wastes are characterized with drastically different properties. Understanding the residue characteristics is indispensable for selecting an appropriate reprocessing strategy. It is noteworthy that the prolonged storage of these residues is often associated with continuously worsening environmental conditions, land occupation, and increased risk of dam failure. Therefore if recovery of critical metals is not achievable in the current circumstance, other residue reutilization options have to be considered, such as used in building materials or water treatment with purification technologies.

An effort should be made to localize and correctly identify mining residues, such as old tailings, abandoned mines and stockpiles, sources of acid mine drainage, abandoned metallurgical wastes, and others. A summary/database compiling maps, available historical records, and issued permits can be a useful tool for the identification of sites eligible for material reprocessing and CRM extraction or for further remediation.

Chapter 2 was dedicated to the appropriate methods of residue sampling and characterization, as different residue categories necessitate different sampling and characterization approaches. The characterization of mine residues in the view of mineral recovery must provide the following information:

- the occurrence of recoverable minerals and their sources,
- the possible distribution of recoverable minerals inside the waste deposit,
- the mechanisms of metal enrichment,
- geometallurgical properties,
- possibilities for CRM recovery,
- recommended reprocessing methods, and
- anticipated impacts of a site re-intervention.

If a geoenvironmental assessment is also in the scope of the characterization, the assessments should include aspects, such as the likelihood of occurrence of waste waters, the type of chemistry expected, impacts, and leaching pathways (International Network for Acid Prevention, 2018).

The sampling methods address diverse strategies for assessing the suitability of CRMs' recovery, including screening, detailed characterization, determination of acid rock drainage generation and wastewater, and the implementation of a geometallurgical approach. The significant advantage of geometallurgical approach was strongly emphasized in this chapter. The methods for characterizing mine residues are a selection of geochemical, mineralogical, and other techniques that can be used either in field environments (e.g., portable X-ray fluorescence, infrared spectroscopy) or in the laboratory (e.g., Inductively Coupled Plasma-based techniques, scanning electron microscopy) to study the main properties of the waste material. Other techniques used for the remote characterization, such as Earth observation, were also addressed. Approaches for data analytics and the impact of digitalization in the characterization of mine residues are briefly discussed. Overall, this chapter aims to help practitioners and researchers to implement better practices in the sampling and characterization for the revalorization of mine residues.

Despite the diversity of techniques and instruments, significant challenges can affect the success of a characterization campaign. For example, the lack of documentation or historical data about waste dumps can hinder the planning for the sampling works and bring considerable uncertainties. Furthermore, the outcomes of a study depend on the quality and representability of the sampled material. Achieving those two aspects can be a difficult task in environments where accessibility for workers and machines is troublesome. On the other hand, the possibility of acquiring different types of data at various scales demands high skills from researchers to make decisions. Data analytics and digitalization become then an integral part of the characterization tasks. Researchers should choose the combination of techniques suitable for the type of material subjected to characterization while providing complete information for the stated aims. In this sense, there are significant opportunities for developing a combined approach for material characterization, both at the technical level (e.g., physical combination of instruments) and in the data analysis.

Chapter 3 was dedicated to the processing and extraction of CRMs from residues, the available technologies, and novelties. The technologies were discussed for the recovery of the following CRMs: antimony, bismuth, cobalt, gallium, germanium, rare earth elements, indium, magnesium, platinum group metals, scandium, tantalum and niobium, tungsten, vanadium, lithium, and titanium. One of the conclusions that can be drawn from this chapter is that the use of conventional mineral processing and metallurgical technologies (e.g., magnetic separation, flotation, and leaching) for reprocessing of mining wastes, tailings, and metallurgical residues is not uncommon. In combination with novel reagents, enhanced equipment, and performance-improving technologies, classical technologies represent a valuable tool for CRMs' preconcentration and recovery from the residue streams. Another important observation is the extensive use of hydrometallurgy or a combination of pyro- and hydrometallurgical methods in waste reprocessing.

It was observed that the developing technologies are often limited to a technology readiness level (TRL) 4 (laboratory testing). It is essential to encourage and fund the upscaling, pilot plant testing, and research on process limitations/operational issues/proof of concept to successfully introduce the technology in the industry.

This chapter also covered bauxite residue and red mud reprocessing initiatives launched in the European Union (TRL 5 and above) aiming to convert these residues into sellable final products and/or recover CRMs and base components.

Chapter 4 covered the authorization and legal aspects of residue storage and reprocessing. The Directives and Laws at European level concerning the management of mining residues were discussed in detail. The focus was made on the instruments adopted by the EU to guarantee health, safety, and environmental protection. The authorization issues, occurring at European and country levels, were addressed, highlighting the operations from some representative countries. Based on this information, a critical analysis of the effective authorization issues for residues reprocessing was made.

This chapter aimed to describe and put in evidence the state of the art of the European and National legislations over the topic of mining wastes, highlighting the procedural difficulties and barriers for potential investors to obtain research permits and later authorizations for recovery of CRMs from stockpiles and tailings. At the same time, the authors proposed some potential solutions, taking advantage of the notable case studies. Further studies and applications could pave the way for advanced and shared legislative and financial initiatives at the European level to support the transition to a more resilient mechanism for sourcing of CRMs.

The conducted research shows how, at the moment, there is still no common legislative framework, aimed to favor recovery and reprocessing. However, many seeds have been planted, which are expected to lead to multiple active operations in the near future, mainly pushed by Green Deal and European ecological transition.

Chapter 5 provided an overview of the economic, environmental, and social implications of CRMs extraction from mining, mineral processing, and metallurgical residues while identifying the most appropriate methodologies to assess them. This chapter described the methodologies, such as material flow analysis, life cycle assessment (LCA), life cycle costing, and social LCA, which could be implemented to support decision-making, case by case, in the prefeasibility phase (at a low TRL level) of mining residue reprocessing, within an eco-design approach. This chapter highlights the importance of adopting a multidisciplinary approach and the relative skills to measure the impacts in the three spheres of sustainability: the environmental, economic, and social. An overview of the economic and environmental issues related to residue processing was presented. This overview described both the potential impacts of these processes in the economic and environmental spheres and identified the potential interactions of recovered CRMs with the market of primary materials. Ultimately, it highlights the economic and environmental strengths and weaknesses of these circular approaches and provides a systematic methodological approach.

This chapter aimed to demonstrate that the recovery of secondary materials from mining, mineral processing, and metallurgical residues can be sustainable in both economic and environmental terms. The authors described the tools that enable to assess of how economically viable and environmentally sustainable these processes are, displaying a concrete opportunity for circular economy and sustainable development while addressing a possibility of sourcing CRMs from deposits within the EU.

Overall, this work presented a comprehensive overview of the current knowledge about the opportunities and challenges of recovering CRMs from mining residues. By reviewing the technical and societal aspects of the extraction of CRMs from secondary resources, this book supports and advises the development of new projects, contributing to the safe, responsible, and resilient supply of the raw materials from mineral resources demanded by our society. It also highlights the critical aspects required to ensure the successful sourcing of CRMs that are not yet fully addressed, which must be the focus of future research initiatives and applications.

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