

TECHNOLOGIES FOR RECYCLING CRITICAL RAW MATERIALS FROM MINING WASTE

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ABSTRACT. Critical raw materials (CRMs) are essential for advanced modern technologies, such as renewable energy, electric vehicles, and the electronics industry. However, their limited availability and reliance on external sources present significant economic and strategic challenges. Mining waste is increasingly recognised as a potential secondary source of valuable materials. The main technological approaches to metal extraction and recycling are studied, including hydrometallurgy, bioleaching, and geopolymerisation, and their advantages, limitations, and applicability are assessed. A comparative analysis of these technologies is presented in terms of their efficiency and environmental impact. The European Union's regulatory framework, which promotes the recycling and reuse of critical raw materials, is also analysed, along with specific examples from Bulgaria and other European countries.

Keywords: mining waste, critical raw materials (CRMs), recovery.

ТЕХНОЛОГИИ ЗА РЕЦИКЛИРАНЕ НА КРИТИЧНИ СУРОВИНИ ОТ МИННИ ОТПАДЪЦИ

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РЕЗЮМЕ. Критичните суровини играят ключова роля в развитието на съвременните технологии, включително във възобновяемата енергия, електромобилността и електрониката. Ограничената им наличност и зависимостта от външни доставки създават значителни икономически и стратегически предизвикателства, превръщайки минните отпадъци в перспективен вторичен ресурс.

В тази връзка се разглеждат основните технологични подходи за извличане и рециклиране на метали от минни отпадъци, включително хидрометалургия, биоизвличане и геополимеризация. Анализирани са техните предимства, ограничения и области на приложение, като е направен сравнителен анализ по отношение на ефективността и въздействието върху околната среда. Разгледана е регулаторната рамка на Европейския съюз, насочена към насърчаване на рециклирането и повторното използване на критични суровини, като са представени и конкретни примери от България и други европейски държави.

Ключови думи: минни отпадъци, критични суровини, рециклиране.

Introduction

Critical raw materials (CRMs) are a group of materials of high economic importance that are also highly vulnerable to global supply disruptions (European Commission, 2023). They are indispensable to high-tech industries, including electronics manufacturing, renewable energy systems, electric vehicles, and defense applications (Gunn, 2014; Blengini et al., 2020). Several rare metals and metalloids, such as rare-earth elements (REEs), lithium, cobalt, antimony, tungsten, and graphite, are characterised by limited geographic distribution, technically demanding extraction processes, and significant environmental challenges associated with their production and waste management (Ali et al., 2017; European Commission, 2023).

Mining operations generate significant amounts of mining waste, including tailings ponds, slag, waste dumps, and landfills, which are traditionally viewed as environmental and economic problems (Lottermoser, 2010). At the same time, these wastes contain residual amounts of valuable elements, making them a potential secondary resource when recycling and reuse technologies are applied (Binnemans et al., 2018). The European Union promotes circular economy and sustainable resource management strategies through policies that balance economic efficiency, environmental security, and social responsibility (Korhonen et al., 2018; European Commission, 2019, 2020).

This article aims to provide a scientific and technological analysis of the possibilities for integrating mining waste into the circular economy through innovative methods for recovering valuable elements, with a particular focus on hydrometallurgical, biotechnological, and geopolymerisation approaches, taking into account EU regulatory frameworks and their applicability.

Mining Waste and Potential for Secondary Utilisation

Mining waste represents complex multi-component systems characterised by high heterogeneity in mineralogical composition, particle size distribution, and physicochemical properties (Lottermoser, 2010; Kossoff et al., 2014). This heterogeneity results from both the primary geological characteristics of the ore bodies and from the technological processes used in the extraction and beneficiation of minerals.

Depending on their origin and mode of formation, mining wastes can be classified into several main categories:

1. Tailings – these are finely dispersed residues generated during the flotation process and other ore enrichment methods. They are characterised by a high specific surface area, which increases reactivity and the potential for secondary metal recovery. Tailings often contain residual concentrations of base and precious metals (Cu, Zn, Pb, Ag), as well as critical raw materials, including rare earth elements, whose extraction was not economically viable during the initial processing. Additionally, they may contain sulphide minerals (e.g., pyrite and chalcopyrite), which are susceptible to intense oxidation and provide a suitable environment for biotechnological extraction methods.

2. Slags – formed as a byproduct of pyrometallurgical processes, they are characterised by a relatively stable amorphous or crystalline structure rich in silicate and aluminosilicate phases (SiO_2 , Al_2O_3 , CaO). Although initially considered inert waste, modern research shows that slags may contain residual amounts of metals and can be used as a raw material for the synthesis of geopolymer materials. Their application in the construction industry and in the stabilisation of

contaminated sites reduces the need for primary raw materials and limits landfilling.

3. Waste rock dumps – coarse-grained waste materials generated during open-pit or underground mining that contain low but often economically significant concentrations of metals. Due to their large volume and relatively low degree of processing, these materials represent a long-term potential resource for secondary extraction through combined technologies, including hydrometallurgical and biotechnological approaches. Furthermore, sulphide minerals can be a source of acid mine drainage, necessitating their controlled management. Geochemical and mineralogical studies conducted in several regions of Bulgaria—including Kardzhali, Madan, Panagyurishte, and Zlatitsa—confirm the presence of significant quantities of residual metals and critical raw materials in mining waste. Similar results have been reported in other European regions, highlighting the pan-European potential for the secondary utilisation of such resources. From a resource efficiency perspective, mining waste should be viewed not as end products of mining operations, but as secondary raw material streams that can be integrated into production cycles through the application of appropriate technological solutions. Their recycling reduces the need to exploit primary deposits, optimises the use of natural resources, and limits the environmental impact. In addition, implementing integrated approaches to mining waste management creates opportunities to reclaim and reuse affected sites, thereby improving the ecological condition of areas with a history of mining activity. In this context, the transformation of mining waste into a secondary resource is becoming a key element of modern strategies for the circular economy and the sustainable management of mineral resources.

Technological Approaches for the Recovery of Critical Raw Materials

Modern approaches for extracting critical raw materials (CRMs) from mining waste are based on a combination of physicochemical, chemical, and biotechnological processes. The primary goal is to achieve maximum recovery while simultaneously minimising resource and energy costs. The choice of a specific technology depends on several factors, including the mineralogical composition, particle morphology, degree of mineral oxidation, and the presence of associated elements that may inhibit or catalyse the extraction processes (Lottermoser, 2010; Vera et al., 2022).

Hydrometallurgy

Hydrometallurgy is a set of processes for extracting metals using aqueous solutions containing acids, bases, or complexing agents. This approach is particularly effective when processing finely dispersed materials, such as tailings, where the high specific surface area facilitates mass transfer processes (Free, 2013).

The hydrometallurgical process flow involves several sequential stages:

- 1) Leaching – the main stage in which metals transition from the solid phase to a soluble form. Depending on the mineral composition, different reagents are used:
 - Acid leaching (H_2SO_4 , HCl) of sulphide and oxide ores;

- Alkaline leaching (NaOH , Na_2CO_3) of aluminium and certain rare metals;
- complexing agents (e.g., cyanides or thiosulphates) for precious metals.

The kinetics of the process are determined by factors that influence the dissolution rate and mass transport, such as temperature, pH, leaching-agent concentration, and other parameters.

- 2) Purification and separation of the solution involves techniques, such as solvent extraction (SX), ion exchange, and membrane processes. These methods enable selective separation of target metals (e.g., Co, Li, REE) from accompanying impurities.
- 3) Extraction – it is carried out by electrolysis, chemical precipitation, or crystallisation, yielding pure metal or salt forms.

A significant advantage of hydrometallurgy is its high selectivity and the ability to recover metals from low-grade ores and low-concentration secondary resources (Habashi, 1999; Free, 2013). However, its limitations include the generation and management of secondary waste streams, as well as the use of chemical reagents that may require subsequent treatment, recycling, and environmental control (Botz et al., 2006; Binnemans et al., 2013).

Bioleaching

Bioleaching is a biochemical process in which microorganisms catalyse redox reactions that promote the dissolution of metals from the mineral matrix. This approach is based on the metabolic activity of acidophilic chemolithotrophic microorganisms, which use inorganic compounds as energy sources (Rendón-Castrillón, et al., 2023; Oziegbe et al., 2026). Among the most commonly used microorganisms are *Acidithiobacillus ferrooxidans*, *Leptospirillum ferrooxidans*, and *Acidithiobacillus thiooxidans*. These microorganisms oxidise ferrous iron and reduced sulphur compounds, forming ferric iron (Fe^{3+}) and sulphuric acid (H_2SO_4), which play a crucial role in the dissolution of sulphide minerals. The main mechanisms include:

- 1) Direct mechanism – microorganisms attach to the mineral surface and promote the direct oxidation of sulphide minerals;
- 2) Indirect mechanism – microorganisms oxidise Fe^{2+} to Fe^{3+} , which subsequently acts as an oxidising agent and chemically dissolves the sulphide minerals.

Bioleaching is successfully applied in the extraction of copper, nickel, cobalt, gold, and uranium from low-grade ores and waste. The process can be implemented in various configurations, including heap leaching, bioreactors, or *in situ* technologies. The advantages of the method include low energy consumption, the ability to process large volumes of waste, and relatively low environmental impact. Limitations include slow kinetics, dependence on optimal conditions (pH ~1.5–3.0, temperature 20–45°C), and the need to control microbiological activity (Kara et al., 2023; Roberto et al., 2022; Vera et al., 2022).

Geopolymerisation

Geopolymerisation represents an innovative approach for transforming aluminosilicate waste materials into stable inorganic polymers through alkaline activation. The process proceeds through the dissolution of the amorphous phases and

subsequent polycondensation, resulting in a three-dimensional Si–O–Al structure (Tian et al., 2020).

The main stages include:

- Alkaline activation – addition of strong alkaline solutions (NaOH, KOH, Na₂SiO₃) that dissolve the silicate and aluminosilicate components;
- Gel formation and polycondensation – formation of a geopolymer gel, which subsequently cures into a stable structure;
- Solidification and structuring – development of the material's mechanical properties and durability.

Geopolymerisation is not aimed at the direct extraction of metals, but rather at stabilising and encapsulating potentially hazardous elements, such as Pb, As, and Cd, within a stable matrix. It makes it particularly suitable for managing waste with elevated environmental risk. Additionally, the resulting geopolymer materials can be used in construction as an alternative to traditional cement products, thereby reducing the carbon footprint and enabling the efficient use of secondary raw materials (Lazorenko, et al., 2021).

To sum up, the technological approaches discussed demonstrate a high degree of complementarity and can be combined into integrated technological schemes. Such approaches enable the simultaneous extraction of valuable components and the stabilisation of residual materials, aligning with modern principles of resource efficiency and the circular economy.

Comparative analysis of technologies

Technologies are analysed in a tabular form below:

Technology	Efficiency, %	Applicability	Advantages	Limitations
Hydro-metallurgy	70–90	Tailings ponds, finely ground ores	High selectivity, extraction of multiple metals	Hazardous chemicals, wastewater treatment
Bioleaching	50–75	Sulphide ores and waste	Low energy consumption, environmentally friendly process	Slow kinetics, sensitivity to pH and temperature
Geopolymerisation	30–50	Slag, silicates, waste materials with high Al/Si	Production of construction products, waste stabilisation	Does not result in direct metal extraction

This comparative analysis shows that the choice of technology must take into account not only the waste's chemical composition but also environmental and economic efficiency.

Regulation and policies in the European Union

The European Union's (EU) policy on critical raw materials (CRMs) is based on an integrated approach combining the principles of resource efficiency, strategic autonomy, and sustainable development. The development of low-carbon technologies, digitalisation, and the defence industry drives the

growing global demand for critical raw materials. The EU is developing a comprehensive regulatory and strategic framework to diversify supplies, increase domestic production, and promote recycling and the reuse of resources.

Critical Raw Materials Act

The Critical Raw Materials Act (CRMA) is a key instrument in the EU's policy to ensure security of supply and reduce dependence on external suppliers (European Commission 2023). It introduces specific quantitative targets by 2030, including:

- at least 10% of annual CR consumption to be met through domestic production;
- at least 40% of processing to take place within the EU;
- at least 15% of consumption is to be covered through recycling.

The regulation also provides for the creation of strategic projects that receive expedited administrative procedures and priority access to funding. Particular attention is given to projects for extracting CRMs from secondary sources, including mining waste, tailings ponds, and industrial residues. In this context, the CRMA encourages the application of innovative technological solutions, such as hydrometallurgy and bioleaching, to enable cost-effective recovery of metals from low-grade materials.

Directive 2006/21/EC on the management of waste from the extractive industries

Directive 2006/21/EC establishes the legal framework for the management of waste from the extractive industries, with the primary objective of preventing or minimizing adverse effects on the environment and human health (European Parliament & Council of the European Union, 2006). It introduces requirements for:

- the development of waste management plans;
- the classification of waste facilities (including high-risk Category A facilities);
- the monitoring and control of facilities such as tailings ponds;
- preventing incidents and accidents, including through the application of best available techniques (BAT).

Of particular importance is that the directive encourages the reuse of mining waste when technically and economically feasible. In recent years, there has been a trend toward integrating the principles of the circular economy into its implementation, including by promoting the recovery of residual metals from landfilled materials.

The European Green Deal

The European Green Deal is a strategic framework for transforming the EU economy towards climate neutrality by 2050 (European Commission, 2019). It focuses on increasing resource efficiency, reducing the carbon footprint of production processes, and closing material loops through recycling and reuse. The Green Deal is closely aligned with the Circular Economy Action Plan, which identifies the circular economy as a key policy priority. Within this framework, mining waste is increasingly regarded as a potential secondary resource, the valorisation of which can help reduce environmental pressures and enhance the security of supply of strategic raw materials.

Funding and Research Initiatives – Horizon Europe

The Horizon Europe program is the EU's main instrument for funding research and innovation for the period 2021–2027,

with a significant portion of resources directed toward the sustainable management of CRs and the development of innovative technologies for their extraction (European Commission, 2021). The EU's regulatory framework on critical raw materials is characterised by a high degree of integration between legislative instruments, strategic policies, and financial mechanisms. This multidisciplinary approach creates a favorable environment for the development of innovative technologies to extract CRs from mining waste and supports the transition to a sustainable, resource-efficient economy. In this context, the secondary utilisation of mining waste is emerging as a key element of the European strategy to ensure raw material independence and achieve climate goals.

Conclusion

The integration of mining waste and critical raw materials into the circular economy is a necessary strategic approach amid global resource scarcity and growing industrial demand. Hydrometallurgical and biotechnological processes, combined with geopolymerisation, offer the opportunity to extract valuable metals while minimising environmental impact. The long-term implementation of these technologies requires clear regulatory guidelines, institutional support, and active participation from research organisations and the industry. Implementing integrated approaches will help build a sustainable, self-sufficient, and competitive industry in Bulgaria and the EU, reducing dependence on external supplies and strengthening resource security.

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