Recycling and Reuse of Mine Tailings

Subjects: Mining & Mineral Processing

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Mining is an important industry, accounting for 6.9% of global GDP. However, global development promotes accelerated demand, resulting in the accumulation of hazardous waste in land, sea, and air environments. It reached 7 billion tonnes of mine tailings generated yearly worldwide, and 19 billion solid tailings will be accumulated by 2025.

beneficiation slag flotation construction material

1. Introduction

The products of mining activity are essential not only for the subsistence of modern society but also for its improvement. It can be reflected on the impact of the absence of products in our daily lives, such as aircraft, ceramics, computers, building materials, medicines, agricultural products, asphalt, electronic products, metals, and paints [1][2]. Substantial mining activity is usually correlated with a region's development, such that geologically privileged regions can count on a considerable part of their GDP from this activity [3]. For example, the European extractive industry includes more than 17,500 companies employing more than half a million people, and the development of the western United States was primarily due to the mining industry [4].

The activities involved in the intricate process of mining range from metal extraction (precious metals, ferrous alloys, and nonferrous materials), mineral beneficiation (gypsum, salt, kaolin, sulfur, and phosphate), fuels (hard coal, steam coal, petroleum, and coking coal), smelting, refining, and remediation [5][6][7]. The process of extraction produces significant amounts of wastes, typically consisting of (i) solid wastes in the form of waste rock, clouds of dust, sludges, and slags; (ii) liquid wastes in the form of wastewater and effluents; and (iii) gaseous emissions. Waste generated due to mining activity poses a serious issue due to the large amounts generated, and it is often associated with the risks posed by its storage and environmental management [8].

Global resources are finite, and greater extraction and use of virgin materials put significant pressure on the Earth's resources, critically threatening future generational resource requirements [9]. Furthermore, population growth generates high consumption, putting pressures never seen before on natural resources. Consequently, the mining industry is generating vast quantities of tailings per year, representing one of the more prominent waste producers worldwide, reaching 7 billion tonnes per year [10]. Recent estimates point out that 19 billion solid tailings will be accumulated by 2025, and due to the structural complexity (chemical and physical), 20% cannot be recycled at all [11][12]. Among others, the consequences are apparent in the permanent impacts on soil exposure, vegetation, water sources (major impact), atmospheric pollution, and harming the lives of the population in its surroundings [1]

[13][14][15]. In this scenario, recycling mine tailings can help reduce the number of tailings for disposal. Circular economy, recyclability, recycling, and reuse have been identified as emerging solutions that can drive the multidimensional aspects of sustainability in the mining and metal extraction industries. As the residue is a heterogeneous, complex, and reactive mixture of minerals, each solution has its advantages and limitations of methods that are observed in waste feasibility studies.

In a feasibility study, waste characterization is initially done during mining, where the waste is stored above ground ore prior to treatment. At this phase, the concern is to determine if the residues will cause acid and metalliferous drainage (AMD), saline and sodic drainage, and leaching and mobilization of metals and toxic compounds. AMD is the formation and movement of highly acidic water rich in heavy metals and causes serious environmental problems around the world. It refers to effluents with low pH and high concentrations of hazardous and toxic elements that are generated when sulfide-rich wastes are exposed to the environment [16]. It is especially harmful when mining activity ceases, causing the water table to rise to normal levels, reacting with contaminated acid leachates that settle on rock walls when the AMD is present [17][18][19]. Australia, Canada, and China have 52,324; 10,129; and 5383 abandoned mines, respectively [20][21]. Neutralization, adsorption, ion exchange, membrane technology, biological mediation, and electrochemical remediation techniques have been used with relative success in tackling AMD [22][23][24][25][26]. As a disadvantage of these remediation techniques, they need to be applied for a long time due to the persistence of the reactivity of the elements that form AMD. As a result, prevention strategies have gained the attention of scholars due to their ability to limit the formation of AMD in the early stages [16].

2. Mining and Mineral Processing Wastes

Mining waste refers to all material that is extracted from the ground and processed to varying stages during the ore-processing and enrichment phases, having low or no economic value, as it is considered an unusable mineralized material and hence is stored or discarded rather than processed [27][28]. Usually, these products present themselves as fine suspended materials (1–600 μm), including dissolved metals and reagents, chemicals, and inorganic and organic additives, and are thus stored in the form of slurry in large man-made embankments, commonly referred to as tailings dams. **Table 1** summarizes some types of mine waste, their classifications, and disposal options [29][30][31][32]. **Table 2** shows the main applications of mine tailing identified in the articles.

Table 1. Characterization of mining waste [29][30][31][32].

Types of Mining Waste	Physical Classification of Residues	Environmental Classification	Disposal Options
Rock waste (sterile)/Processing waste • Aqueous solutions	Solid form • Waste rock, dust, sludge, and slag, Liquid form	Chemical and mineralogical composition Physical properties Volume and surface occupied	Tailings dams Exhausted mine pits, In piles, by dry stacking (suitable for areas of high seismic activity, for cold climates) Disposal in paste

Types of Mining Waste	Physical Classification of Residues	Environmental Classification	Disposal Options
• Wastewater • Particulate emissions • Water treatment sludge • Metallurgical slag • Atmospheric emissions Acid mine drainage AMD	• Liquid slag, • wastewater, • effluent Gaseous form	Waste disposal method	Underground backfilling Submarine tailing disposal (STD)

Table 2. Tailings identified and their applications.

Types of Tailings Identified	Application	Number of Articles Analyzed
Iron ore; Copper; Platinum Group Metals; AMD; Zinc; Phosphogypsum; Slag; Red mud; Electric oven powders; Limestone powder; Fly ash and sewage sludge; Clay-based residues; Gold tailings; Marble; Coal combustion	Construction materials	25
Manganese; Phosphogypsum; Platinum Group Metals; Combustion coal; Mine drainage sludge; Limestone powder; Phytoremediated tailings	Agricultural applications	7
AMD-causing tailings	Geopolymers	3
Chromium ore tailings	Automobile catalytic converters; electronic materials; jewelry	3
Sand-based tailings; Platinum Group Metals; Coal combustion; Copper slag	Landfills and source of rare earth elements	3

According to **Table 1**, mining waste can present itself as rock waste from the bedrock that has been mined and transported out of the pit. However, it does not have a metal concentration of economic interest. It is stored in a landfill site near mining production because it is not economically viable to transport to another site [33]. In the processing phase, an ore mill is located at the extraction site to produce the first marketable products (metallic concentrates, sorted ore, and ingots); the residues of this stage are called processing waste. In this phase, various types of waste, such as aqueous solutions, wastewater, and slurry composed of fine-grained particles mixed with additives as well as products of chemical reactions are produced, which need to be stored in ponds for dewatering.

Acid mine drainage occurs when acid, sulfate, and metal wastewater (effluents with a low pH and high toxic element concentration) are released from the ponds into the environment. The mine may continue to generate AMD for decades even after it ceases its operation. It is a huge source of concern due to its high environmental impact [16][34]. Still, in the processing stage, roasting is applied in sulfides to extract metals and remove impurities from the ore. Therefore, toxic gases like SO_2 come out; this is an example of mine waste in the form of atmospheric emissions [35]. Still, one of the residues from the burning of sulfides is classified as slag, and it usually accumulates together with ashes in the vicinity of the production center, rather than in tailings ponds.

Disposal refers to accumulating large amounts of waste in a concentrated area or filling spaces in inoperative mines. Tailings dams are the most common method of deposition of fine tailings from ore grinding. Here, the idea is to dispose of the waste in an optimized, accessible, and environmentally safe way to allow its reprocessing in the future with the advancement of new technologies. Researchers will address some of them in this research. Underground backfilling is the most expensive method; it can only be used away from aquifers, and it is generally an option when geological stability and safety in operations are required. Submarine tailing disposal (STD) consists of the deposition of tailings in underwater marine bodies. Although there is a lot of criticism regarding the risks of the operation, and this has been increasing restrictions on the use of this solution over time [36][37], some researchers emphasize the benefit because the underwater conditions favor the geochemical stabilization of sulfide mineral residues [38].

According to **Table 2**, construction materials are the main applications of mine waste. In this sector, the most significant research is related to additive incorporation in cement for concrete block manufacturing [32][39], followed by brick manufacturing [40][41]. Agricultural products are in second place. Tailings that are suitable for use in agriculture must possess more similar physicochemical, compositional, and morphological characteristics, primarily in being rich in silicates, calcium, iron, and aluminum, among other beneficial elements, to be desirable for soil remediation and remineralization purposes. Several agricultural applications were observed in the articles, such as improving soil structure and crop yield [42], reducing soil erosion [43], treating acidic or metal-rich soils [44][45], or increasing available S and P concentrations in the soil [46].

3. Recovery of Mine Wastes through Reuse and Recycling

Reusing mine waste means using the material in its entirety without processing it in a new application. Recycling, on the other hand, extracts new valuable components from the waste or uses the waste as an input to the manufacture of a valuable product or application through processing [47]

In the different mining phases (exploration, transport, processing, and beneficiation), measures are taken to manage the generated waste. Different parameters such, as geographic, geological, hydrogeological, and climatological disparities, are decisive for addressing the strategies. In the long term, the research and development (R&D) sectors of companies work to improve the efficiency of current exploration methods (drilling and extraction), while in the short term, planners and decision makers embrace management tools, as shown in **Figure 1**, aiming to add value to the production liability and reducing the risk of the operation.

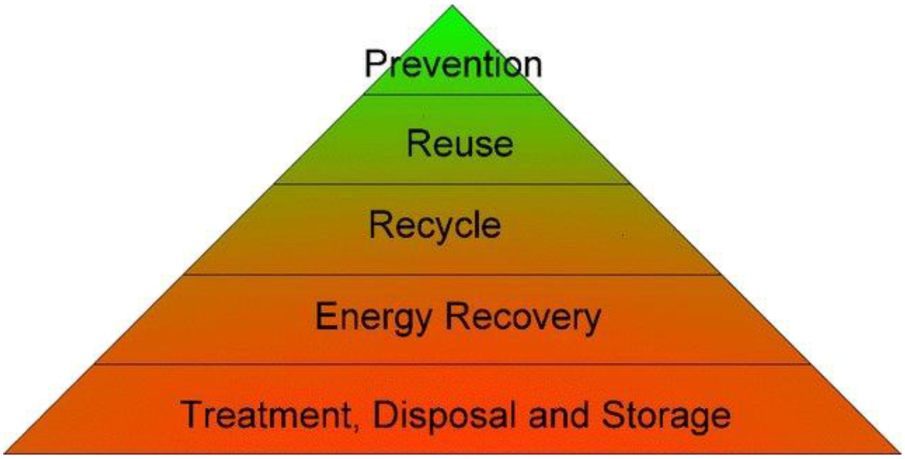

Figure 1. Mine waste hierarchy, adapted from [48].

The triangle of **Figure 1** represents a mine waste hierarchy serving as a guide for prioritizing waste management practices, representing the most favored at the top to the least favored at the bottom. As seen, the minimization of the creation of mine waste is the preferred option, whereas disposal and treatment are the least preferred option. Reuse and recycling are the top feasible options in waste management [47].

For it to be possible to reuse waste, there must be a guarantee of the quality of the material compared to the original condition. In this strategy, there is no biological, physical, or physical-chemical transformation. The advantages are the saving of natural resources and manufacturing of cheaper products.

Recycling, which aims to reintroduce a waste after undergoing transformations in its properties to a particular production chain and serve as raw material for the manufacture of other products, has the following advantages: generation of employment, encouragement of scientific development, and reduction of the need for extraction of minerals in mines, among others. However, the most common practice used in conventional mining is treatment, disposal, and storage, the least favored option.

Despite the consolidation of technologies for treatment, disposal, and storage, there is a growing evolution regarding the use of mining waste recycling, especially in developed countries [49][50][51], where an increase in the number of research activities in this area leads to the belief that structural modification of this pyramid is possible in the future [52][53].

Table 3 shows the main recycling and reuse processes of residues, outlining the advantages and drawbacks of each. These residues are by-products of mining or have an indirect relationship in sharing similar properties and/or composition to mining waste, thus facing similar technical and economic feasibility challenges and opportunities.

Table 3. The relationship between types of mine waste and their main recovery techniques.

Type of Waste	Main Recycling/Reuse Processes	Advantages	Limitations	Citing Articles
Metal waste	Flotation	Large-scale use; effective application in fine minerals; application in non-magnetic ores.	Low recovery when mixed with mud.	Wang et al., 2017 [54]; Ndlovu et al., 2017 [55]; Mackay et al., 2018 [56]; Shengo, 2021 [16]; Kalisz et al., 2022 [57].
	Gravity Separation	No use of chemical products; Relatively little environmental impact except for the disposal of sludge; Operational simplicity; Lower cost than flotation; Application in materials with larger particle size.	Considerable loss of tailings when the method is dense type.	Wang et al., 2017 [54]; Ndlovu et al., 2017 [55]; Rao et al., 2017 [58].
	Magnetic Separation	Low operational cost; Simplicity of equipment; A small amount in the release of waste that can affect the environment.	Application only in waste with the presence of magnetic materials.	Wang et al., 2017 [54]; Ndlovu et al., 2017 [55].
	Solvent Extraction	Economically and operationally feasible to execute in a short time; obtaining elements with high purity; effective in the selective extraction of heavy metals from industrial waste.	Cost, degradation, volatility of solvents.	Ndlovu et al., 2017 [55].
	Biolixiviation (bioleaching)	Microorganisms are used to obtain metals from low-grade ores; High technological potential; Recent technology.	Slow rate; Climate dependent; Containment requirements.	Duarte et al., 1990 [59]; Stanković et al., 2015 [60].
	Amalgamation	An efficient process for extracting larger particle size metals; Simple and inexpensive process.	Limitation in recovering fine-grained materials.	Pulungan et al., 2019 [61].
Gypsum waste	Solvent Extraction	Good selectivity; Obtaining elements with high purity.	-	Cánovas et al., 2018 [62]; Garg et al., 1996 [63].

Type of Waste	Main Recycling/Reuse Processes	Advantages	Limitations	Citing Articles
Metallurgical waste	Acid Leaching	Low energy input; Low investment.	Difficult separation of impurities; Presence of a high volume of acid.	Cánovas et al., 2018 [62].
	Pyrometallurgical Process	Ability to receive zinc-based metallurgical powders.	High thermal energy requirements; Additional steps to recover volatile metals from flue gas.	Matinde et al., 2018 [29]; Ndlovu et al., 2017 [55]; Lin et al., 2017 [64].
	Hydrometallurgical process	Increasing use in recent years; Flexible and economical; Few environmental problems.	Chemical consumption; Separations challenges.	Matinde et al., 2018 [30]; Buzin et al., 2017 [65]; Ndlovu et al., 2017 [55]; Rodríguez et al. 2020 [66].
	Electrometallurgical process	Emerging technology; Smaller scale use.	Materials of construction requirements.	Hansen et al., 2012 [67].
Steel slag	Dry Granulation	More used; More effective; Less environmental pollution.	Lower product value.	Bisio, 1997 [68]; Barati et al., 2011 [69].
	Air Blast Granulation	Metals recovered with higher heterogeneity.	Higher energy consumption.	Bisio, 1997 [68]; Barati et al., 2011 [69].
	Granulation with Liquid Slag Impact	Reduction of energy intensity in the metal production process.	The release of toxic gases; Little possibility of using vitreous slag in materials such as cement.	Barati et al., 2011 [69].

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It is also worth noting that the choice of procedure depends on the physical-chemical characteristics/properties of the residue, in addition to the operational cost to recover these materials from the waste and their environmental impact. Some techniques are already well consolidated, while others are still under development, requiring further research for their use to be on a larger scale.

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