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Review

Recycling and Reuse of Mine Tailings: A Review of Advancements and Their Implications

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Abstract: 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. Adding to this, the legacy of environmental damage from abandoned mines is worrying; in Canada there are around 10,000 abandoned mines, 50,000 in Australia, 6,000 in South Africa, and 9,500 coal mines in China, reaching 15,000 by 2050. In this scenario, restoration techniques from mining tailing have become increasingly discussed among scholars due to their potential to offer benefits towards reducing tailings levels, thereby reducing environmental pressure for the correct management and adding value to previously discarded waste. This review paper explores available literature on the main techniques of mining tailing recycling and reuse and discusses leading technologies, including the benefits and limitations, as well as emerging prospects. The findings of this review serve as a supporting reference for decision-makers concerning the related sustainability issues associated with mining, mineral processing, and solid waste management.

Keywords: beneficiation; slag; flotation; construction material; soil remediation

1. Introduction

The products of mining activity are essential not only for the subsistence of modern society but also for its improvement. We can reflect 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 [5-7]. 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].

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Global resources are finite and greater extraction and use of virgin materials puts significant pressure on the Earth's resources, critically threatening future generational resource requirements [9]. Furthermore, the 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 the more prominent waste producer 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 [1,13-15]. 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 method that are observed in the waste feasibility study.

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 know 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 [17-19]. Australia, Canada, and China have 52,324, 10,129, and 5,383 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 [22-26]. 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].

Recently, as is hereafter reviewed, many researchers have proposed the recycling or reuse of mine wastes due to their potential to offer benefits over reducing tailings levels, thereby reducing environmental pressure for the correct management, and adding value to previously discarded waste. Criticism occurs when some researchers argue that there are more opportunities to reduce the impact of tailings waste in the mining design phase than in the operational or post-processing phases, and the emphasis on post-processing strategies could undermine prevention opportunities [27]. Given the concerns listed, the aims of this review are to present recent technological advancements in recycling and reuse of mining tailings, to explore the environmental and economic implications of these strategies, and finally to discuss future perspectives for mine waste remediation technologies.

2. Methodology

A total of 90 published articles between 1990 and 2022 were analyzed. These papers were retrieved through scholarly databases such as Scielo, Scopus, Google Scholar, Science Direct, ResearchGate, and Web of Science. The keywords used in the literature search included: "mining tailings," "waste," and "recycling techniques" with "metal recovery", "construction materials", "new applications", "sustainable mining", and "agricultural fertilizers".

The articles were analyzed according to a series of characteristics. Initially, the types of tailings sources were identified, such as lead, zinc, copper from overload, rock waste, processing tailings, metallurgical slag, and water treatment residuals, among others. It was also noted the disposal and treatment types of the mining waste. Next, the degree of the environmental impact of mining operations, for example: the suppression or prevention of vegetation; the removal of large amounts of fertile soil; the contamination of water sources, waters in rivers or in reservoirs by oil, grease and heavy metals; the modification of the water-flow regimen; air pollution; and the risks arising from the accumulation of tailings in containment barriers. Finally, the recovery options observed in the articles were summarized, outlining the advantages and disadvantages of each application.

3. Discussion

3.1. 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, hence is stored or discarded rather than processed [28,29]. Usually, these products present themselves as fine suspended materials (1–600 μm), including dissolved metals and reagents, chemicals, 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 [30-33]. Table 2 shows the main applications of mine tailing identified in the articles.

Table 1. Characterization of mining waste [30-33].

Types of mining waste	Physical classification of residues	Environmental classification	Disposal Options
Rock waste (sterile) / Processing waste •Aqueous solutions •Wastewater •Particulate emissions •Water treatment sludge •Metallurgical slag •Atmospheric emissions Acid mine drainage AMD	Solid form •waste rock, dust, sludge, and slag, Liquid form •Liquid slag, •wastewater, •effluent Gaseous form	Chemical and mineralogical composition Physical properties Volume and surface occupied Waste disposal method	Tailings dams Exhausted mine pits, In piles, by dry stacking (suitable for areas of high seismic activity, for cold climates) Disposal in paste Underground backfilling Submarine tailing disposal (STD)

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 the 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 [34]. 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 low pH and high toxic elements 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 [16,35]. 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 [36]. 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. Tailing dams is 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. We will address some of them in this article. 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 [37,38], some authors emphasize the benefit because the underwater conditions favor the geochemical stabilization of sulfide mineral residues [39].

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

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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 [33,40], followed by brick manufacturing [41,42]. 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 [43], reducing soil erosion [44], treating acidic or metal-rich soils [45,46], or increasing available S and P concentrations in the soil [47].

3.2. 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 [48]

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.

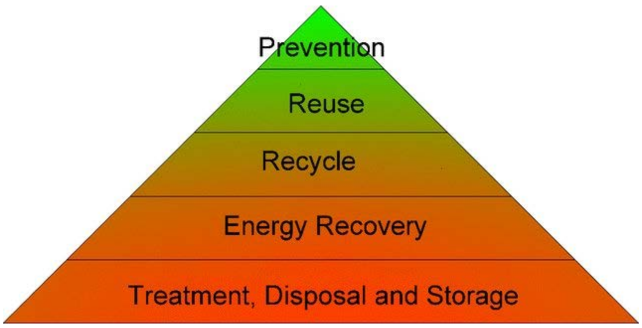

Figure 1: Mine waste hierarchy modified from [49].

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, 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 [48].

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, reduction of the need for extraction of minerals in mines, among others. However, the most common practice used in conventional mining is the 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 [50-52] 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 [53,54].

Table 3 shows the main recycling and reuse processes of residues outlying 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 [55]; Ndlovu et al., 2017 [56]; Mackay et al., 2018 [57]; Shengo, 2021 [16]; Kalisz et al., 2022 [58].
	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 [55]; Ndlovu et al., 2017 [56]; Rao et al., 2017 [59].
	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 [55]; Ndlovu et al., 2017 [56].
	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 [56].
	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 [60]; Stanković et al., 2015 [61].

	Amalgamation	An efficient process for extracting larger particle size metals; Simple and inexpensive process.	Limitation in recovering fine-grained materials.	Pulungan et al., 2019 [62].
Gypsum waste	Solvent Extraction	Good selectivity; Obtaining elements with high purity.	-	Cánovas et al., 2018 [63]; Garg et al., 1996 [64].
	Acid Leaching	Low energy input; low investment.	Difficult separation of impurities; Presence of a high volume of acid.	Cánovas et al., 2018 [63].
Metallurgical waste	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 [30]; Ndlovu et al., 2017 [56]; Lin et al., 2017 [65].
	Hydrometallurgical process	Increasing use in recent years; Flexible and economical; Few environmental problems.	Chemical consumption; Separations challanges.	Matinde et al., 2018 [31]; Buzin et al., 2017 [66]; Ndlovu et al., 2017 [56]; Rodríguez et al. 2020 [67].
	Electrometallurgical process	Emerging technology; Smaller scale use.	Materials of construction requirements.	Hansen et al., 2012 [68].
Steel slag	Dry Granulation	More used; More effective; Less environmental pollution.	Lower product value.	Bisio, 1997 [69]; Barati et al., 2011 [70].
	Air Blast Granulation	Metals recovered with higher heterogeneity.	Higher energy consumption.	Bisio, 1997 [69]; Barati et al., 2011 [70].
	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 [70].

It is important to emphasize that even if a residue is not directly linked to mineral exploration, it entered the subsequent analysis of this Section because its use in the composition of mineral residues in recycling processes was identified in several analyzed articles, signaling its importance. For example, metallurgical waste in [32,71,72] and steel slag in [73-76].

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.

Next, we will detail the main types of waste and their respective methods of use, whether in recycling or reuse.

3.2.1. Metal waste

In the past, the prices of non-ferrous metals were somewhat lower than they are today, and this is the main reason why the mining industry has left significant quantities of these in tailings dams around the world. The increased reprocessing of copper tailings is

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becoming an increasingly logical decision, with a sufficiently high content of valuable components so that tailings can be economically exploited, and new technologies for copper extraction and recycling are being developed [30]. It is also possible to recycle iron, copper, zinc, and gold mining waste to obtain bricks, tiles, and lightweight aggregates [12]. Regarding copper recovery, bioleaching has been widely used, where thermophilic bacteria are used to recover copper and other valuable metals [60,61].

Furthermore, copper waste has been used with relative success replacing granite used in road and highway pavement concretes and brick production [32,33,77,78] In these studies, the suitability of copper ore tailings as an additive mixture in concrete preparation was tested by replacing common Portland cement at different grades. Up to 20% is saved when we use copper ore tailings instead of Portland cement. The copper tailings produced in this way had good strength and durability characteristics. Regarding the anticorrosive characteristics and cost reduction, the use as an additive product, rather than as raw material, was considered a good option [79]. Copper slag is also being used in the manufacture of roof tiles, mine filling materials, and granular materials [80].

In most cases, iron ore tailings have fine granulometry, high silica content, iron oxides, alumina, and other smaller minerals [81]. This composition facilitates its use in the construction industry [82]. However, this waste generates water and soil pollution in the form of dust, leaching water runoff from mining waste, and infiltration of iron-contaminated water, which consequently affects living things [83]. When using iron ore tailings as mortar, up to 85% of tailings can be applied with good results, with the option of manufacturing different types of products, such as paving blocks and masonry blocks [84]. Clay and shale are essential in producing bricks and must be subjected to a high firing temperature [85]. Extracting materials consumes a lot of energy, negatively affecting the environment and releasing a worrying amount of residue and greenhouse gases [41,86]. Thus, it is interesting to defend the development of ecologically correct materials and construction processes, where iron tailings represent an option of raw material to produce bricks.

Similar to copper waste, iron ore residues can be mixed in concrete, floors, and ceramic tiles with relative mechanical and physical, and chemical performance [87-89]. The compressive strength of concrete from iron ore tailings (Figure 2) showed an improvement of 11.56% compared to concrete with conventional aggregates, showing that it is possible to obtain quality materials from mineral tailings in relation to certain mechanics properties [87]. However, some characteristics disqualify processing residues as aggregates such as metal composition, variability, particle size, leaching of trace metals, and adjacent chemical reactions that can generate unwanted acids [56]. Because the iron content in this type of material is very low, reprocessing can become complicated due to the huge volume of waste generated to extract an economically viable amount of iron ore. This excessive volume of waste will require good storage management.

Figure 2. (a) fine and (b) coarse iron ore tailings, and (c) tailings aggregate concrete. Source: [87]. CC-BY.

Sulfides from mining oxidize more easily in tailings facilities, exposing tailings to air and water. This disturbing phenomenon in the mining industry is known as acid mine drainage (AMD). A solution to reduce the formation of acid mine drainage is the use/recycling of mine waste into building materials and geopolymers [90]. In addition, there are other industrial materials with recovery potential from tailings, for example, sulfur, sulfuric acid, metallic pigments, and sulfates, calcium carbonate and magnesium hydroxides, agricultural materials (e.g., fertilizers), and adsorbents [91].

3.2.2. Gypsum waste

Gypsum is by far, one of the most materials produced in the world. The total amount of unwanted by-product, the phosphogypsum (PG) solid waste produced up to 2006 is estimated at 6 billion tonnes, of which 2.2 billion tonnes (37%) were produced in the United States [63].

Due to the high content of calcium, phosphorus, and sulfur, PG has been successfully used as a soil amendment, in addition to having a fertilizer value due to the ammonium sulfate content [11]. Recent studies [92], have used mixtures of cement - OPC (Ordinary Portland Cement) and phosphogypsum in the stabilization of soils with high water content and low strength, known as degraded soils. The authors characterized different types of sedimentary soils, with different plasticity indexes, where the soil sludge was mechanically mixed with cement and phosphogypsum powder, obtaining a homogeneous paste. The specimens obtained from the above procedure were subjected to different tests such as unconfined compressive strength (UCT), pH measurement, SEM, and XRD. Significant improvements were obtained in terms of mechanical strength, density improvement, and obtaining ettringite (AFt), as the main cementitious product of the pozzolanic reaction between cement, phosphogypsum and clay minerals.

It is economically attractive to develop studies to seek the use of PG in construction materials, roads [93], agriculture [63], re-obtaining mineral resources that were previously underexploited, or in environmental applications. However, it is important to know that the percentage of use is still low (15%), and the remainder, in most cases, is accumulated in abandoned storage areas [63,94].

3.2.3. Metallurgical waste

Metallurgical powders are generated from materials added in foundry furnaces. They are heterogeneous mixtures and oxides with a relative degree of complexity [56]. Generally, the two main options for recovering valuable metals from ferrous powders are pyrometallurgical and hydrometallurgical processes. The principal gain of pyrometallurgical processes is the ability to process in a viable way metallurgical dust containing high amounts of Zn [56,65].

However, they are special processes that require high temperatures, efficient dust filtration systems, and volatilized return steps for the additional recovery of metals present in the flue gases [56]. There are advantages related to hydrometallurgical processes, which puts it highly rated compared to other technologies. Flexibility, economy, low emission of toxic gases, dust, and noise are some of the advantages. As a disadvantage, we can mention the high-water consumption, in addition to making it impossible to use it in products with high added value such as glass, and ceramic materials, among others. Due to the considerable concentration of Pb, Cr, Zn, and Cd, these residues are classified as hazardous. Thus, its disposal is controlled through pre-treatment or stabilization [56,66,95–97]. Although these powders are economically valuable, recycling can be done directly, but the process is generally limited by the accumulation of harmful metals and other materials.

3.2.4. Steel slag

The energy consumed in high-temperature metal processing is distributed between metal, slag, off-gas, and natural losses to the atmosphere. The thermal energy of the slag accounts for about 10 and 90% of the output energy, depending on the slag-to-metal ratio and the discharge temperature. Ferrous slags account for over 90% of the output thermal energy. The available energy associated with slag where slag alone constitutes 50% of that energy. Thus, the investigation to recover part of this energy is recurrent, as well

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as the development of more energy-efficient processes based on the physical and chemical aspects of the slag. These methodologies include dry granulation processes, air jet granulation, impact granulation of solid slag, and centrifugal granulation [70,69]. Liquid slag is also studied as it has a good property of sensitive heat recovery through chemical methods [70].

Solidified metallurgical slag contains significant amounts of metal-based contaminants, which can harm the environment. For example, the presence of dissolved toxic metal species such as chromium in stainless steel, steel, and ferrochromium alloy slag can cause serious environmental problems [56,98,99].

The recovery of slag from metallurgical processes is recurrent due to the number of consolidated techniques. Application of slag as building materials [32], and in the manufacture of ceramics [100,101] is often identified. However, the recycling and reuse of the slag are strongly hampered by the presence of dissolved toxic metallic elements [31].

Radiation monitoring of waste from the blast furnace is necessary, and there is already a study that proves it established safe values for building materials, which indicates that the cement compounds studied do not have a significant effect on increasing the exposure risk of the population [102]. Metallurgical slag also has great potential as a raw material in building new engineering materials, for example, glass ceramics, porous ceramic materials, ceramic bricks, functional zeolites for wastewater treatment, and refractory materials.

Blast furnace slag is used in the composition of cement, adding special properties such as increased mechanical strength, morphology, and resistance to abrasion [103-105]. Converter slag (obtained by the pig iron industry) is not used as much for recycling due to high free lime content, but there is potential if the free lime is stabilized by carbonation [106,107].

The slag from an electric arc furnace (EAF) and slag from desulfurization and slag skimming (SDSS) generated by steel mills have been used as a fine aggregate or concrete filling material in the construction industries [12,108], but beneficiation treatment can be either a requirement due to unsuitable properties or to improve properties, safety, and market value, as exemplified in Figure 3. Excellent results were observed for slag rejects obtaining good homogeneity, good mechanical properties, and the possibility of up to 40% cement reduction in the application in concretes [109].

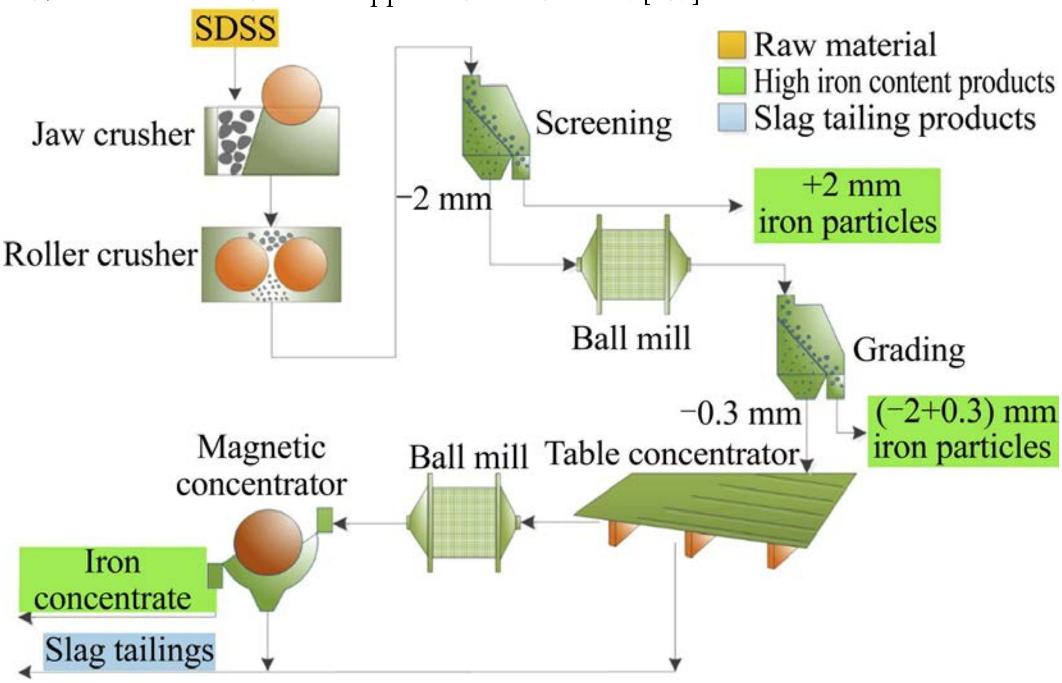

Figure 3. Flowsheet of SSDS beneficiation experiment. Source: [108]. CC-BY-NC-ND.

In the mining process itself there is the formation of slag, a waste material produced in ore extraction. This mining waste can be used as construction material (road construction), both in infrastructure and in the reclamation of land damaged by mining [110,111]. However, the use of slag from metallurgical processes is more common for the recovery/recycling of tailings from mining, so steel slag is among the more commonly used waste types [32,74,112]. For example, there is a study that was carried out recycling gold mining waste by slag atomization, being a process without harmful environmental impacts. However, a thorough evaluation of the process is necessary to obtain various types of materials, such as asphalt concrete, among others [74].

3.3. Future perspectives of mine tailing remediation techniques

Mining waste generation and disposal must always be reviewed and updated periodically. Although several methods can be suggested for recycling mine waste, the key point is the presence of up-to-date feasibility and technical, operational, economic, and environmental studies in line with local legislation. The waste recycling technique used depends on the production capacity required, the type and volume of final product generated, and the public health and environmental regulations applicable to the production process [113,114]. Figure 4 shows a decision-making organogram for aiding in the design of upgrading processes for mine wastes [114].

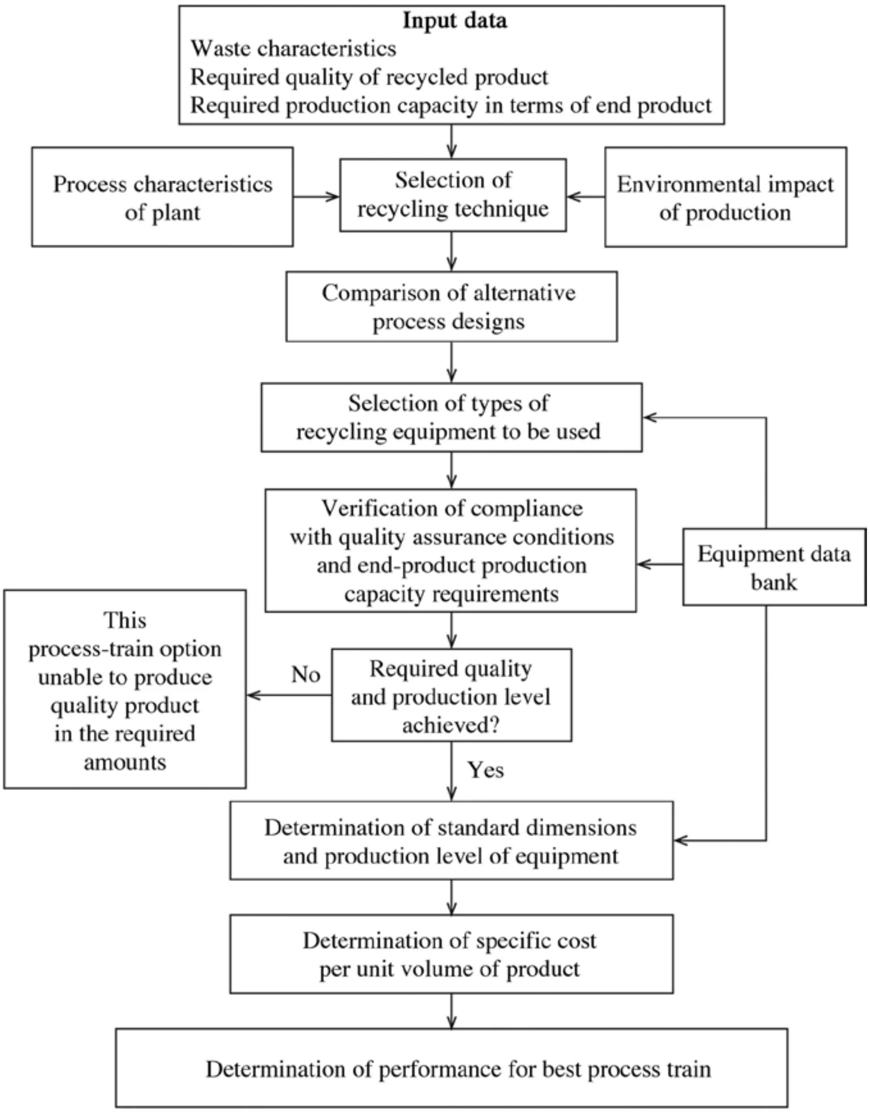

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Figure 4. Flow chart for mineral waste recycling process-train design algorithm. Source: [114]. Reused with permission from Springer Nature (5342261298332).

Geopolymerization is a promising technology that is currently being studied to convert tailings or dumps into new raw materials. It consists of mixtures of a solution of sodium silicate and sodium hydroxide to which water is added. Iron ore tailings are blending in geopolymer as fine aggregates, fillers, and precursors forming new materials that can be used as construction materials such as roads and highways. This procedure can be used to recover several types of tailings, mainly: copper (binder materials, bricks, and road-construction materials), iron (binder materials, bricks, and backfills for building foundations), phosphate (binder materials), among other applications [115].

A practical example of the above is the study carried out by Figueiredo et al. [116], where a commercial metakaolin (MK) based geopolymeric cement was prepared as precursor material, and sodium silicate, Na_2SiO_3, (SS), and sodium hydroxide, NaOH, (SH) as activators. Three different iron ore tailings (IOT), obtained from flotation processes of three mines located in the province of *Quadrilátero Ferrífero*, in the state of Minas Gerais, Brazil, were added to the above, to use the mine tailings as filler. Subsequently, the chemical composition of the MK and IOT was evaluated by X-ray fluorescence analysis (XRF) with a Philips spectrometer. The incorporation of tailings into the geopolymer cements promoted an increase in compressive strength which is promising for the development of better mine tailings management practices for alternative applications, but the authors state that further research is required to better understand the interactions between geopolymer matrices and backfills from mine tailings.

Another remarkably recent technology is the one that uses microorganisms, but it is still in the laboratory study phase. In addition, the lack of greater investment affects the development of this study, being also a chronic problem in a broader way. Although the economic return is satisfactory, there is a need for an initial investment that often limits advances in this area. To achieve a long-term aesthetic solution, the use of live plants or microorganisms/biomass, which can be implemented in situ for remediation of tailings and mill tailings, is proving to be a promising strategy. In this recent phenomenon, Phyto stabilization has emerged as an alternative recovery technique for the stabilization of environmental toxins using green plants, which is proving to be economical, self-sustaining, and aims to rehabilitate the entire terrestrial as well as aquatic ecosystems [14,117].

It is remarkable that a greater effort is still needed to increase the recycling of solid waste. Mine tailings technologies can be improved, where there are many discrepancies in recycling rates and application of waste reduction technologies between a few developed countries (US, Japan, Western Europe, China) and most countries [118,119]. It is necessary to involve industrial waste in use because of its potentially valuable consumer properties to develop and implement low-waste technologies in cooperation with scientific organizations [120].

4. Conclusions

In recent years, several adequate resource management approaches have been used for recycling mine waste, most notably: the recovery of valuable minerals and metals, production of cost-effective building materials, and preparation of soil modifiers and agricultural fertilizers [121-124].

It is notable that a greater concern of the countries for better use of this waste to provide profitability to the use of these components in various areas of application. From the analyzed works, studies were observed in relation to the use of waste in almost 40 countries, highlighting mainly: China, India, the United States, Spain, Japan, Australia, the United Kingdom, Russia, Canada, and South Africa. Many of these countries produce large amounts of solid waste, but in parallel, they are evolving the issue of waste recycling, with the aim of reducing environmental impacts.

Despite the high demand from the construction industry (1.5 billion tonnes), the use of tailings as construction material does not reach 1% in volume [119]. This situation occurs due to factors such as the value of building materials being relatively low compared to other products with higher added value, and transportation costs [107,122].

In this review, successful or potentially implementable approaches covered predominantly included those where the material properties resulted in ecologically friendly and low-cost resource recovery, compared to traditional materials. To this end, it has been clear from the literature that recycling or recovery of tailings from mines has had applied as construction materials, despite low profitability and agricultural applications, but that is limited to tailings having non-hazardous compositions and being in reasonably close locations to their end-use.

To tackle these wastes, engineered technologies to re-process them are needed, and the most innovative examples of these from the literature have been bioleaching, flotation, and magnetic separation. Even then, limitations arise when it comes to the complexity of the recovery process, or of the mineral composition itself, and the still generation of residues (sludges and wastewaters) with burdensome contaminants (metals, ligands, surfactants, acids, microbes, etc.).

There is a need for more research on the recycling and recovery of tailings from mines, with little R&D being observed in different chemical compositions and geotechnical characterization of tailings. Tailing recycling is thus still incipient in most countries in terms of volume, and local regulatory pressures have been the main drivers for action in wealthier nations and those with strong environmental advocation groups.

Despite a relatively vast literature on the research subject of mine tailing reuse and resource recovery, the subject also remains quite broadly tackled. This leaves several research gaps in need of more attention, mainly those concerning technological transfer from academia to practice, and improved efficiency in the recovery and use of valuable compounds from tailings, including chromium, cobalt, manganese, nickel, bauxite, aluminum, zinc, silver, feldspar, bentonite, among others.

The reuse of mining waste involves integrated and properly controlled management, which does not always lead to the desired results. To improve the current situation, the integration of different methodologies and available technologies will be necessary, and inspiration could be found from the principles of process intensification [125], which despite their origins in the field of chemical engineering have the potential to bring disruptive solutions to the fields of mineral and solid waste processing.

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