*Review*

# Recycling Strategies of Mine Tailing, and Its Technical and Practical Considerations

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**Abstract:** Mining is an important industry that provides products and services through infrastructure systems worldwide. However, the global development promotes the steady growth and accelerated demand for minerals, resulting in the accumulation of hazardous waste in land, sea and air environments and, consequently a series of environmental and health problems. Restoration techniques from mining tailing have become increasingly discussed among scholars 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. This review paper critically explores available literature on the main techniques of mining tailing recycling, and discusses leading recycling 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 from the mining activity are essential for the subsistence of modern society. 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]. Waste generated due to mining activity poses a serious issue due to the large amounts generated, even up to 65 billion tonnes per year, and is often associated with the risk posed by its storage and environmental management [2]. Global resources are finite and greater extraction and use of virgin materials puts greater pressure on the earth's resources critically threatening future generational resource requirements [3], therefore, the growing demand in the consumer market leads to the need to recover minerals due to the scarcity of natural resources.

Substantial mining activity is usually correlated with the development of a region, so that geologically privileged regions can count on a considerable part of their GDP from this activity [4]. Garbarino et al. (2020) [5], show that the European extractive industry includes more than 17,500 companies employing more than half a million people. Consequently, mining is of great importance in the development of several countries. For example, historians report that the development of the western United States was primarily due to mining. Moreover, in Europe, in the same way, mining has always been the main guarantor of mineral inputs for the industry [1]. The main elements of ferrous alloys are manganese, chromium, titanium, and nickel. The primary non-ferrous materials produced in recent years are aluminum, bauxite, copper, and zinc. The principal precious metals are silver and gold, producing a large amount of waste, and these products have a major impact on the environment and can cause serious environmental problems [6,7]. The main industrial minerals are gypsum, salt, kaolin (used in ceramics), sulfur (chemicals in agriculture) and phosphate (production of agricultural fertilizers). The main mineral fuels are: hard coal, steam coal, petroleum and coking coal [8]. On the other hand, the growing demand in the consumer market entails a need to recover discarded minerals due to the scarcity of natural resources and the high volume of consumption mainly originated by population growth, companies in this sector needed to adapt through more efficient processes, requiring innovative technologies to manage mine waste [9].

In these contexts, it is known that there is a production of thousands of tonnes per year of tailings, the mining industry is the largest waste producer worldwide, representing for between 5 and 7 billion tonnes per year only of mine tailings [10]. The primary method of disposal currently used is in dams, followed by the tailings dam [11,12]. The impact of mining is apparent and permanent on soil exposure, altering vegetation, affecting water sources (major impact), atmospheric pollution and harming the lives of the population in its surroundings. [1,13–15]. About these disposals, Azcue (2012) [16], claims that waste in solid form is the main responsible for the environmental impact. These events have increasingly led to the use of mining tailings, either by employing new technologies for processing these "ores" with undesired contamination, poorer grades or by using them for other applications.

To choose the appropriate recycling method, it is necessary to analyze characteristics such as the geology of the mineral, physical properties, environmental impact, and economic viability. It is usual to recover metallic compounds in the leaching solution using several procedures [1]. Another way to use ores from rock residues and mining tailings, in general, is through their use in building construction [17]. Mining tailing restoration techniques have become increasingly discussed among scholars in the last decades (Figure 1) due to their potential to offer benefits by generating useful raw material again and reducing the amount of waste to be handled.

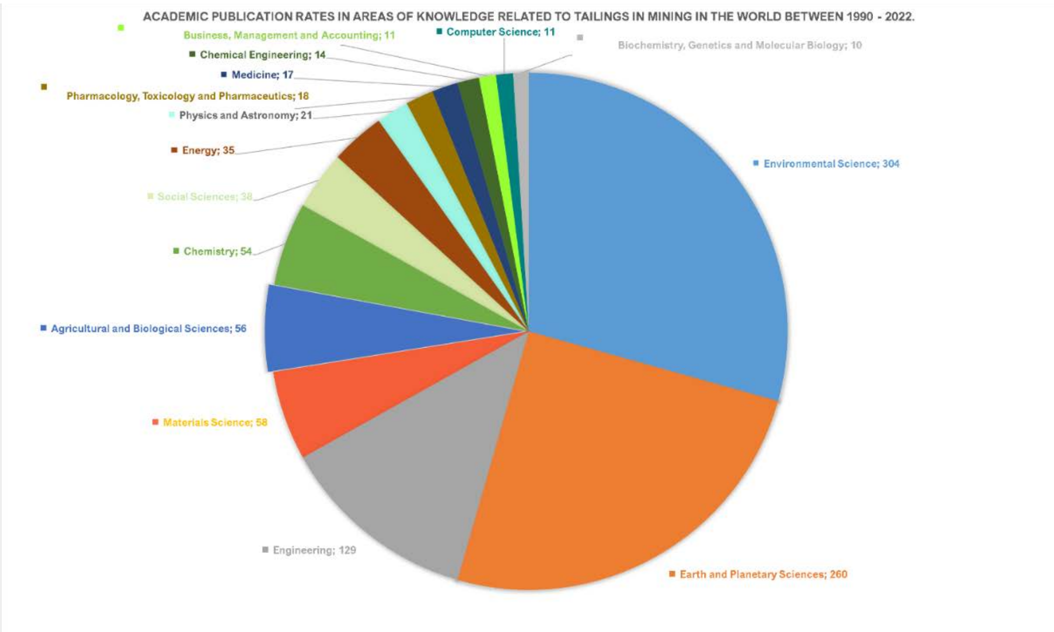


**Figure 1.** Indexes of academic publications in areas of knowledge related to tailings in mining in the world between 1990 - 2022. Data source: Scopus.

Given the concerns listed, the objective of this review is to present developments on: (i) the environmental problems of the formation of mine tailings; (ii) options to recycling tailing resources; (iii) future perspectives for mine waste remediation techniques. The structured review is organized as follows. In the methodology section we discuss the search strategies, study selection criteria, and the main statistics. In the discussion section we analyze critically the main results related to environmental concerns of mining waste, recovery and utilization techniques and future trends of remediation strategies. Furthermore, we provide a comparison of studies related to social, environmental, economic, health and safety perspectives. Finally, in the conclusion section we state the implications of the findings, limitations, and ideas to advance the subject.

## 2. Methodology

This article is a critical review of literature which comprises 74 papers published between 1990 and 2022 retrieved from the web through search engine 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”. In the reference lists of the chosen articles, other studies that adhered to the theme were collected, and Google Scholar was used to identify reports, conference proceedings or other technical information related to the recycling of mining waste.

The 74 published 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, water treatment, among others. It was also observed the disposal and treatment types of mining waste. Afterwards, the degree of environmental impact of mining operations, for example, the suppression or prevention of vegetation, removal of large amounts of fertile soil, contamination of water sources, waters in rivers or reservoir by oil, grease and heavy metals, modification of water-flow regimen, air pollution and mostly 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. Environmental problems of the formation of mine tailings*

The mining industry generates several categories of waste. Some types are overload, rock waste (sterile), mineral processing tailings (generated in mineral processing processes, being rock, soil, loose sediments, fine/ultrafine particles), metallurgical slag, wastewater, water treatment sludge, acid mine drainage (acid, sulfate, and metal wastewater release), gaseous and particulate emissions and post- consumption [18]. Residues can be presented in different forms, for example, in solid form (waste rock, dust, sludge and slag in liquid form (liquid slag, wastewater, and effluents), and in gaseous form [18]. In general, it is possible to say that the tailings can be disposed of in underground mines, in exhausted mine pits, in piles, by dry stacking (suitable for areas of high seismic activity, for cold climates, by disposal in paste, and tailings dams (upstream, downstream, and “in the centerline” type). There are both hazardous and non-hazardous inorganic solid waste. The first represent the majority, the second comes mainly from secondary processes of extraction of non-ferrous materials such as Al, Fe, Zn, and Cu [19].

There is a large production of tailings from mineral extraction. A study by Jones and Boger (2012) [20], claims that the mineral industry is number one in the world's waste production, it is about 65 billion tonnes/year, of which 14 billion are tailings consisting mostly of fine particles, smaller than 150 μm. There are approximately 5-7 billion tonnes of mine tailings generated each year around the world [21]. Other sources report that waste quantities are estimated to be around 20-25 billion tonnes/year worldwide [22]. Scholars estimate 19 billion solid tailings by 2025 [23]. Due to the structural complexity (chemical and physical), 20% cannot be recycled. They were remaining for these cases, safe disposal [19,24]. Although the analysis focused on the period between 1990 and 2022, there are studies such as the one conducted by Shengo (2021) [15], which dates the evolution over time of tailings management practices between 1900 and 1990, as shown in Figure 2.

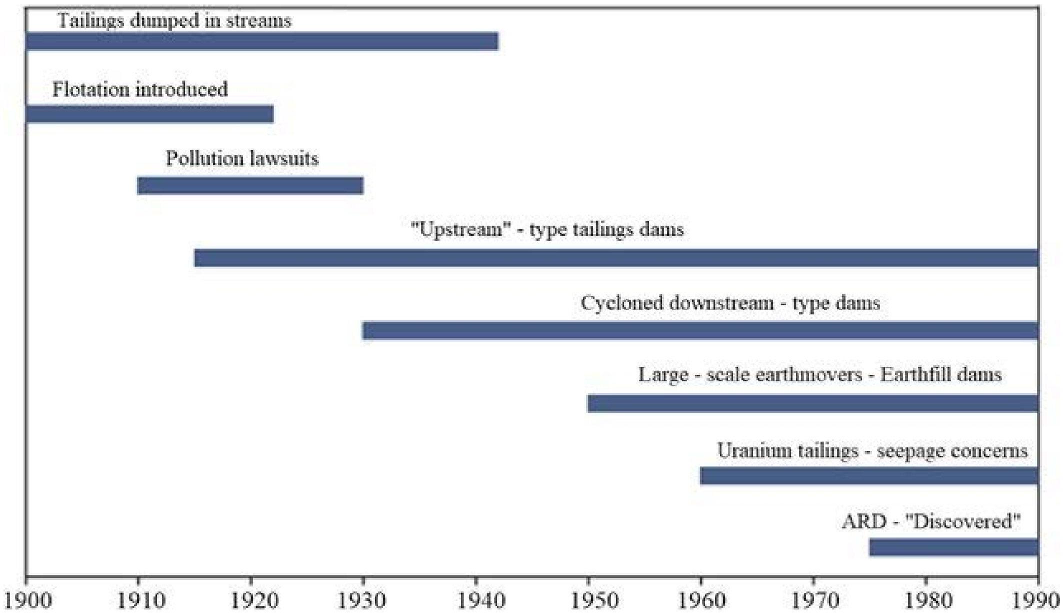


**Figure 2.** Evolution over time of tailing management practices. Source: [15]. Re-used with permission from Springer Nature (5338590274398).

Importantly, mining dumps can contaminate ground and surface. In addition to toxicity, the high complexity of the waste often makes it difficult to recycle. Thus, the variety of electronic sensors combined with high-speed processors that can be programmed to recognize certain characteristics of the ores, transforming a group of mixed waste into several easily recyclable categories. Therefore, the implementation of an optical separator, being applied in recent years, brings several benefits: separation is fast, simple, malleable, economical, and a less polluting process [25]. Previously, authors such as Gülcan & Gülsoy (2018) [26], reviewed and validated the viability of mineral analysis by VIS (visible light, color) and NIR (near infrared) classification. Making the two previous ones, the most used techniques in the classification of minerals, because they present advantages at the time of clearly observing the spectra of VIS and NIR wavelengths and therefore, the molecular and crystalline structures of the minerals.

Additionally, resources such as water, air, besides being explosive and flammable [6], can be affected by solid wastes, putting at risk the stability of their own storage facilities [21]. In this way, it becomes even more important to find the satisfactory destination of the tailings, to minimize problems in the containment dams. Most countries have legislation in force for the disposal of mineral residues and tailings dams. However, accidents involving such structures are not rare, especially since the 1990s, and along with them, economic, social, and environmental damage [27–30]. Even nowadays, existing construction with outdated design, operation, and maintenance guidelines, despite the evolution of legislation and increased inspection. The cost of accidents, which involves, among other factors, damage to property, studies and reports, indemnities and legal fees, staff time, and loss of remuneration, is noticeably greater than the cost of prevention. The European database on mine incidents is incomplete. To make sense, these data need to be supplemented with information contained in published articles and reports from government, organizations, and companies. There is a high concentration of accidents in the USA (North America), Chile (South America); The United Kingdom (Europe). An important parcel of mine incidents is related to meteorological issues. In the second place It is the mismanagement and inappropriate human operations at Dam. Failure in management process accounted for 10% of worldwide incidents and 12% of European cases. It is noteworthy that most failures occurred in active dams [31]. According to the International Council on Mining and Metals (ICMM), the poor implementation of standards, guidelines and risk control in mine tailing storage facilities is the main concern of environmental managers, not the technologies for physical stability of dams, which are already widely available [32]. From then onwards, it was natural for companies to have greater disclosure of information due to several joint actions, such as Mining and Waste Safety and the United Nations Program for the Environment (UNEP). Approximately since 2020, ICMM, has also been working on the effective implementation and consolidation of the Global Industry Standard on Tailings Management (Figure 3). Therefore, the multidisciplinary and articulated work has become even more visible and necessary, in order to comply with and exceed the established standards [33].

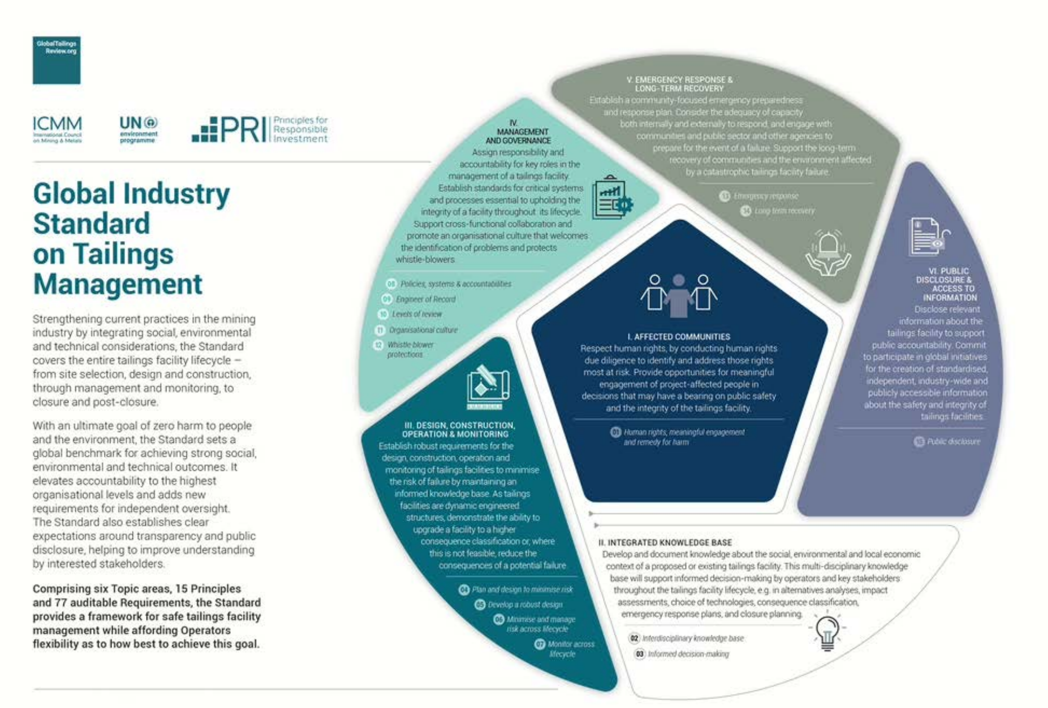


**Figure 3.** Comprehensive outline of the 6 areas, 15 principles, and 77 auditable requirements for effective understanding and application of the Global Industry Standard on Tailings Management. Source: [33]. © ICMM 2022, re-used with permission.

It is worth noting the various unwanted effects resulting from mining, such as environmental changes (water, air, and noise pollution), land-use conflicts, depreciation of surrounding properties, generation of the degraded areas, disturbances to urban traffic, among others. Several regulations and policies were put into practice to control the destination or recycling of mine waste, but without effective success [34, 35]. Dust discards from marble production, for example, in riverbeds and around production facilities cause reduced soil permeability. Furthermore, fine particles result in poor soil fertility due to increased alkalinity [19]. Nigeria, South Africa, The United States, Australia can be highlighted as countries concerned with the modernization of legislation to reduce environmental impacts, especially knowing the presence of radioactive elements such as uranium, zirconium, thorium, among others. Another worrying example occurred in Zambia, where the effect of lead poisoning on children was revealed, with blood lead levels more than the reference value of 5 μg/dL [36].

Given these various potential impacts of the generation and inadequate disposal of mine tailings, over time, efforts have been made to establish effective technologies to prevent, reduce and manage this waste along the production chain. Next, we will discuss various mine waste recovery and reuse strategies.

### *3.2. Options to recycling tailing resources*

Mining and its industrial waste are considered to have low or no economic use options remaining to be allocated in landfill [37]. However, mine tailings have attracted attention due to new technologies, growth in the recycling market, and pressure from society to tackle environmental problems arising from poor storage [18]. Table 1 shows some types of solid waste verified in the articles studied with their respective applications after the use of waste recovery or recycling techniques. According to Table 1, the main products are construction and agricultural materials, in addition to other applications on a smaller scale. Compared to the residues used in constructions materials, 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, aluminum, among other beneficial elements, to be desirable for soil remediation and remineralization purposes.

**Table 1.** Types of tailings and their applications.

| Types of mining tailings | 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 | 24 |
| Manganese; Phosphogypsum; Platinum Group Metals; Combustion coal; Mine drainage sludge; Limestone powder; phytoremediation | Agricultural applications | 7 |
| AMD | Geopolymers | 3 |
| Chromium Ore Tailings | Automobile catalytic converters; electronic materials; jewelry | 3 |
| Sand-based tailings; Platinum Group Metals; Coal combustion; Copper slag | Landfills | 2 |

To maximize the return on investment, miners focus on two main objectives: increasing safety in operations as accidents have the potential to cause irreversible damage, and the correct storage and disposal of waste, which can significantly burden operations [16]. The selection of one method or another for tailing disposal depends on the nature of the mining process, the geological and topographical conditions of the region, the mechanical properties of the materials, the environmental impact of tailings contaminants, and the climatic conditions of the region. Table 2 shows the main recovery processes for each type of mine tailings, showing the main characteristics of each method. It is worth noting that the choice of procedure depends on the physical-chemical characteristics/properties of the tailings, in addition to the operational cost to recover these metals 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.

**Table 2.** The relationship between types of tailings and main recovery techniques.

| Type of mining tailings | Main Recovery 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 [96]; Ndlovu et al., 2017 [35]; Mackay et al., 2018 [99]; Shengo, 2021[15]; Kalisz et al., 2022 [2]. |
| | 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 [96]; Ndlovu et al., 2017 [35]; Rao et al., 2017 [97]. |
| | 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 [96]; Ndlovu et al., 2017 [35]. |
| | Solvent Extraction | Economically and operationally feasible to execute in the short time; obtaining elements with high purity; effective in the selective extraction of heavy metals from industrial waste | - | Ndlovu et al., 2017 [35]. |
| | Bioxylivia tion | Microorganisms used to obtain metals from low-grade ores; High | - | Duarte et al., 1990 [39]; Stanković et al., 2015 [40]. |

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| | | | | |
|---|---|---|---|---|
| | | technological potential; Recent technology. | | |
| | Amalgamation | Efficient process for extracting larger particle size metals; Simple and inexpensive process. | Limitation in recovering fine grained materials. | Pulungan et al., 2019 [101]. |
| **Gypsum waste** | Solvent Extraction | Good selectivity; Obtaining elements with high purity; | - | Cánovas et al., 2018 [60]; Garg et al., 1996 [61]. |
| | Acid Leaching | Low energy input; low investment. | Difficult separation of impurities; Presence of the high volume of acid | Cánovas et al., 2018 [60]. |
| **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 [18]; Ndlovu et al., 2017 [35]; Lin et al., 2017 [64]. |
| | Hydrometallurgical process | Increasing use in recent years; Flexible and economical; Few environmental problems | - | Matinde et al., 2018 [18]; Buzin et al., 2017 [68]; Ndlovu et al., 2017 [35]; Rodríguez et al. 2020 [98]. |
| | Electrometallurgical process | Emerging technology; Smaller scale use. | - | Hansen et al., 2012 [100]. |
| **Steel slag** | Dry Granulation | More used; More effective; Less environmental pollution. | - | Bisio, 1997 [72]; Barati et al., 2011 [71]. |
| | Air Blast Granulation | Metals recovered with higher heterogeneity. | Higher energy consumption. | Bisio, 1997 [72]; Barati et al., 2011[71]. |
| | 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[71]. |

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Reuse is usually operated near to the mining site and includes sand with concrete and utilized as landfill, and clay-based residues for making bricks and floor tiles. Next, we will detail the main types of waste and their respective methods of use.

3.2.1. Metal waste

A worrying amount of slag, dust, sludge, and scrap is associated with copper smelting and refining activities [19]. 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 becoming an increasingly logical decision, with a sufficiently high content of valuable of valuable components so that the tailings can be the tailings can be economically exploited, and new technologies for copper extraction and recycling are being developed [38]. Regarding copper recovery, bioleaching has been widely used, where thermophilic bacteria are used to recover copper and other valuable metals [39,40].

Oluwasola et al. (2015) [41], evaluated the suitability of using electric arc furnaces from copper mine waste as a substitute for granite used in road and highway pavements. In application to obtain cement [42–45], copper ore tailings in the production of concrete and bricks [46]. 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% are economized 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 a raw material, was considered a good option [47]. Guohua et al. (2011) [45] used tailings from copper mines and coal gangs as substitutes for clay to make cement clinker. Copper slag is also being used in the manufacture of roof tiles, mine filling materials and granular materials [48].

In most cases, iron ore tailings have fine granulometry, high silica content, iron oxides, alumina, and other smaller minerals [49]. This composition facilitates its use in the construction industry [50]. In addition, 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 [25]. 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 [51]. Clay and shale are essential in the production of bricks and need to be subjected to a high firing temperature [52]. The extraction of these materials consumes a lot of energy, negatively affecting the environment and releasing a worrying amount of residue and greenhouse gases [53, 54]. 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.

According to Kuranchie et al. (2015) [55], Ugama et al. (2014) [56] and Kumar et al. (2014) [57], studies on concrete as well as floors and ceramic tiles can receive percentages of iron ore residues in their composition. Kuranchie et al. (2015) [55], observed that the compressive strength of concrete from iron ore tailings (Figure 4) 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. Some key characteristics disqualify processing residues as aggregate such as metal composition, variability, particle size, leaching of trace metals and adjacent chemical reactions that can generate unwanted acids [35]. 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.

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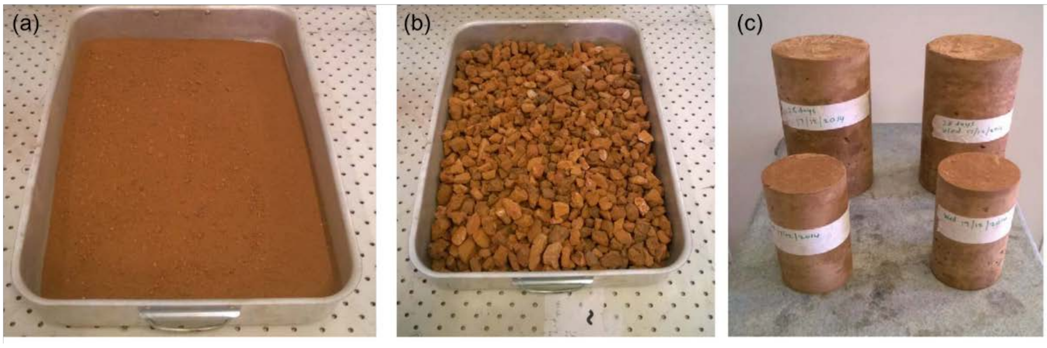


**Figure 4.** (a) fine and (b) coarse iron ore tailings, and (c) tailings aggregate concrete. Source: [55]. CC-BY.

Sulfides from mining oxidize more easily in tailings facilities, exposing tailings to air and water. This disturbing phenomenon for mining industry is known as acid mine drainage (AMD) [58]. A solution to reduce formation of acid mine drainage is the use/recycling of mine waste into building materials and geopolymers [58]. 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 [59].

3.2.2. Gypsum waste

Another very common recovery is waste from the production of gypsum, one of the most produced industrial minerals in the world, where more than 5 tonnes per year are generated from phosphogypsum type waste (plaster, the main component), mainly in the United States [60]. Lime mud, for example, can be recycled to make cement, sand bricks, partition walls, tiled floors, blocks, plaster, fibrous gypsum board, and supersulfated cement [61]. One of the most explored valorization routes is the manufacture of construction materials such as: bricks, cement, plasterboard, or tiles [60, 62].

Phosphogypsum has also been used as a conditioner in calcium and sulfur deficient soils, in addition to having a fertilizer value due to the ammonium sulfate content [23]. It is advantageous to apply this material to improve the soil due to the high content of calcium, phosphorus and sulfur found. [60]. Alcordo and Rechcigl (1993) [63], studied the possibility of using this material as an accessory product in the field.

It is economically attractive to develop studies to seek the use of these residues in the manufacture of construction materials, agriculture, 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%) [60]. Phosphogypsum can be used in road building materials as an additive in the cement production process, but its use is limited due to radiation due to radionuclides, but it can be safe depending on the added content and exposure time [60,65].

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 [35]. Generally, the two main options for recovering valuable metals from ferrous powders are pyrometallurgical and hydrometallurgical processes. The principal gain of pyrometallurgical processes are the ability to process in a viable way metallurgical dust containing high amounts of Zn [35,64].

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 [35]. There are advantages related to hydrometallurgical processes, which puts it as highly rated compared to other technologies. Flexibility, economy, low emission of toxic gases, low emissions of 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, ceramic materials, among others. Due to the presence in considerable concentration of Pb, Cr, Zn and Cd, these residues are classified as hazardous. Thus, its disposal is controlled through pre-treatment or stabilization [35,66–69]. 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

Approximately 6% of all energy consumption on the planet is due to steelmaking activities [70]. The amount of released energy associated with slag is high, above 80% [71]. Thus, the investigation to recover part of this energy is recurrent, as well 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 [71, 72]. Liquid slag is also studied as it has a good property of sensitive heat recovery through chemical methods [71].

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 ferro-chromium alloy slag can cause serious environmental problems [35, 73, 74]. There has been research on the application of slag as building materials [75], and in the manufacture of ceramics [76, 77]. However, the recycling and reuse of the slag is strongly hampered by the presence of dissolved toxic metallic elements [18]. 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 in increasing the exposure risk of the population [78].

Metallurgical slag 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 [19, 79–81]. 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 [102]. The slag from an electric arc furnace (EAF) and slag from desulfurization and slag skimming (SDSS) generated by steel mills has been used as a fine aggregate or concrete filling material in the construction industries [19,82], but beneficiation treatment can be either a requirement due to unsuitable properties or to improve properties, safety and market value, as exemplified in Figure 5. 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 [83].

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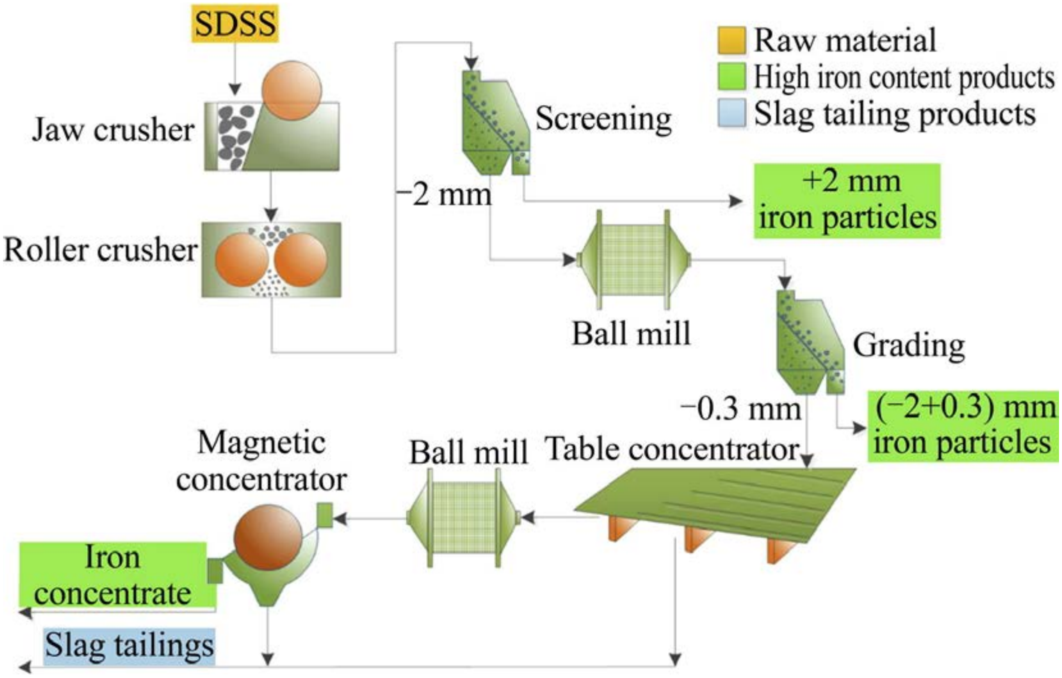


**Figure 5.** Flowsheet of SSDS beneficiation experiment. Source: [82]. CC-BY-NC-ND.

*3.3. Future perspectives of mine tailing remediation techniques*

The generation and proper disposal of waste from mining must always be reviewed and updated periodically. Although there are several methods that 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 produced, and the public health and environmental regulations applicable to the production process [84,85]. Bardovsky et al. (2022) [85] proposed a decision-making organogram for aiding in the design of upgrading processes for mine wastes (Figure 6).

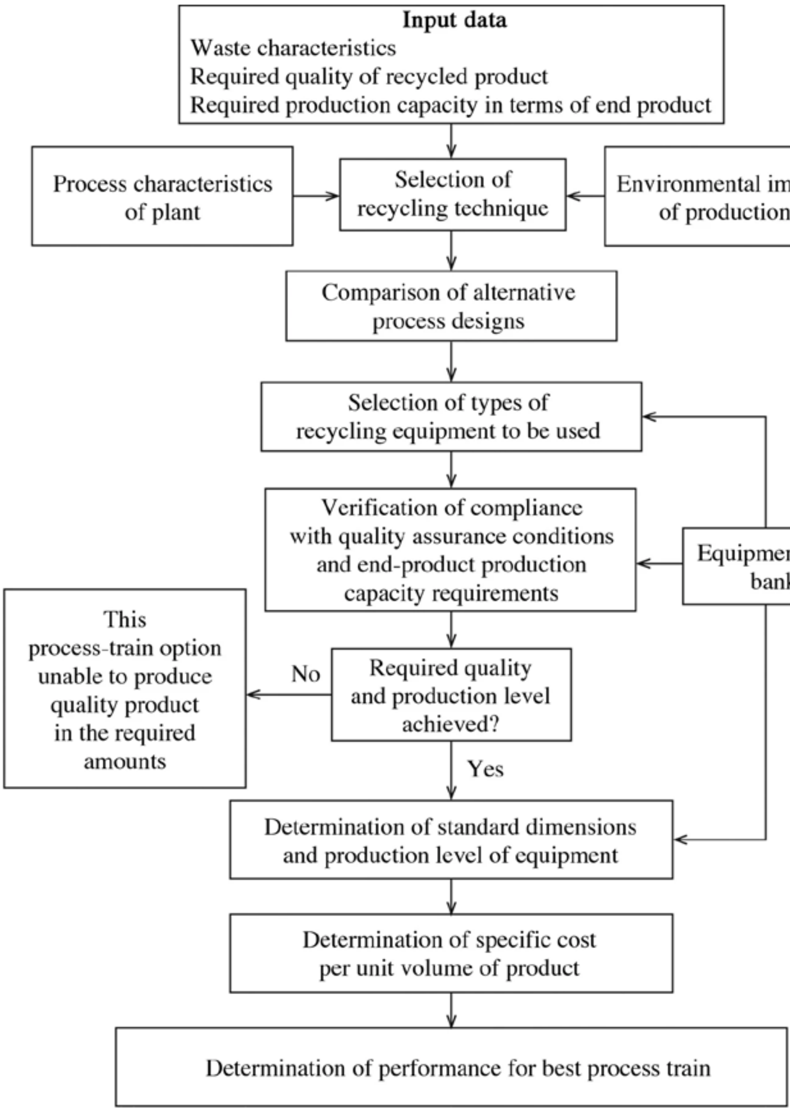


**Figure 6.** Flow chart for mineral waste recycling process-train design algorithm. Source: [85]. Reused with permission from Springer Nature (5342261298332).

Geopolymerization is a new technology that is currently being studied, where this process can convert the tailings or dumps into a new raw material that will be supplied for the construction of infrastructure such as roads and highways [6, 58, 86] This technique is economically viable if the transporting costs incurred by customers of mine waste are kept to a minimum. 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 [87].

Another very recent technology is the one that uses microorganisms, but it is still in the laboratory study phase. In addition, the lack of greater investment also 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 [14]. Most traditional methodologies used for remediation of metal contaminants are expensive and, in addition to being an additional cause of environmental destruction, can be impractical. In order to achieve an aesthetic long-term 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, phytostabilization has emerged as an alternative recovery technique for the

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stabilization of environmental toxins through the use of green plants, which is proving to be economical, self-sustaining, and aiming to rehabilitate the entire terrestrial as well as aquatic ecosystem [88].

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 is much discrepancy in recycling rates and application of waste reduction technologies between a few developed countries (US, Japan and Western Europe, China) and most countries [89, 90]. 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 [91].

## 4. Conclusions

In recent years, several adequate resource management approaches have been used for recycling mine waste; most notably: recovery of valuable minerals and metals, production of cost-effective building materials, and preparation of soil modifiers and agricultural fertilizers [92–94]. However, 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 [90]. 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 the costs caused by transport logistics [90,95].

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, in relation to traditional materials. To this end, it has been clear from literature that recycling or recovery of tailings from mines has had greater application in construction materials and agricultural applications, but that is limited to tailings having non-hazardous compositions and being is reasonably close locations to their end-use. This still leaves a large portion of tailings in many mining regions in the world with no clear use, leading to long-term storage that have been examples of tragedies in recent years when accidents happen. To tackle these wastes, engineered technologies to re-process them are needed, and the most innovative examples of these from literature have been bioleaching, flotation and magnetic separation. Even then, limitations arise when it comes to 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 around recycling and recovery of tailings from mines, with little R&D being observed in different types 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 an 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 [103], 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. Examples include the applications of microwave and ultrasound energy in activating mineral surfaces to facilitate flotation [104,105].

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