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Review

Various Options for Mining and Metallurgical Waste in the Circular Economy: A Review

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Abstract: In the last few years, the mining and metallurgy industry has made concerted efforts to improve waste management through a byproduct recovery strategy, mainly focusing on developing innovative technologies to provide sustainable solutions. This strategy has seen the metallurgy industry exploit more natural resources in waste streams while reducing its environmental impact, making the 'zero-waste' goal possible. As such, the concept of circular economy emerged, which seeks to improve the environmental sustainability of mining operations by recycling and reusing the generated waste as raw materials for producing other new products. This paper aims to analyze the findings from published studies on the treatment and stabilization technologies of metallurgical waste or byproducts for the construction industry. Furthermore, the paper synthesizes information on processes and treatment strategies to beneficiate the waste materials for application in the building and construction sector. Finally, the paper identifies knowledge gaps in the literature, using a comprehensive overview of the superior results achieved by the metallurgical industry and potential synergies with other industrial sectors. In conclusion, the paper presents future opportunities while highlighting specific areas that may be further explored. This review paper is helpful to researchers in the mining waste management discipline to have an aerial view of what has already been achieved in the field to improve the existing processes for environment preservation.

Keywords: solid waste disposal; solid waste management; hazardous waste; sustainable circular economy

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1. Introduction

The mining industry, mainly in South Africa, has been one of the major economic drivers for decades [1]. Generally, mining is a multiple-activity process involving metal extraction, mineral beneficiation, refining, and remediation [2]. Large amounts of waste are produced alongside valuable metals during mining and metallurgical operations. Typically, the waste generated in the mining sites may be in liquid form, such as wastewater and acid mine drainage; solid waste in the form of sludge, slags, and waste rock [3]; other waste types are given in Table 1. These waste streams pose a significant environmental challenge, and poor management may permanently damage the ecosystem and human health. The standard practice in South Africa is that these solid waste streams are disposed of in landfills, exacerbating nearby communities' environmental and health challenges. Furthermore, cost increments and the decreasing space of landfills are steadily forcing researchers to find alternative options for solid waste disposal. Generally, solid waste management is a global problem that affects environmental sustainability, social and economic decline, and ecological deterioration [4]. Canceling the effects of the generated waste from the mining activities requires a robust waste management methodology that includes recycling the waste back into the processing system and the reuse of the waste for different applications [5].

Table 1. Different types of waste are produced in the mining and metallurgy process.

Type of Waste	Description
Acid mine drainage	Wastewater generated from tailings and underground mine work either on active or inactive mining sites.
Metallurgical waste	Slags of material produced in the metal refining process, including smelting, are a byproduct of the process.
Mine tailings	Fine rocks that remain after the metal extraction process; are in a slurry form and deposited in tailings ponds.
Waste rock	They also remain after the mining process, but they are still regarded as rich in minerals but may form acid-mine drainage.
Overburden	A stockpile of rocks and soil from the mining process; has the potential to form acid mine drainage as well.
Waste dust	Particulate dust contains toxic chemicals, such as organometallic compounds, and toxic gases, such as CO, NO_x, CO_2, and SO_x are released during metal processing.

Meanwhile, reusing and recycling the generated waste products and replacing natural raw materials make their impact on the environment less hazardous [6] and minimize the potential of causing harm to humans. Regardless of these types of waste being environmental stressors, the metallurgical processes may integrate the reuse and recycling of this waste to form a circular economy model with no pollution [7]. For example, solid metallurgical waste products, such as blast furnace slag, have proven to be commercially viable construction materials, including in house building blocks, concrete, and road construction [8]. As such, the circular economy model promotes reclaiming precious metals and producing more valuable products for other industries while minimizing waste and land pollution. Moreover, this model seeks to eliminate the destruction of natural land used as dumping sites for solid waste from mining and metallurgical operations [9]. The need for the development of recovery and recycling technologies, investment in infrastructure, the establishment of viable markets, and participation by industry, research institutes, government, communities, and consumers are all considered to be a priority in the circular economy.

Focusing on recycling as the major element in the circular economy approach, waste material recycling is propelled by economic and technological factors [5]. Moreover, recycling may be defined as a practice that uses metallurgical waste as raw materials to produce new valuable products [7]. It could also be a means of processing waste and returning to the material cycle to minimize the contamination of the environment [10]. As asserted by Simate and Ndlovu [3], Figure 1 presents the short- and long-term advantages of employing recycling strategies for metallurgical waste. Furthermore, waste streams can be collected and converted into reused material at the same or even better capacity.

Undoubtedly, the environmental challenges posed in emerging and developed economies are relatively distinctive; however, both economies suffer from technical, economic, social, and legislative impacts [11]. To tackle these problems, one needs to read the literature extensively to compare management strategies, which this paper seeks to achieve to give a comprehensive overview of the literature. The presented review details the treatment options, waste management, and current and novel approaches for metallurgical waste disposal available to fit into the circular economy. Lastly, a proposed integrated system is proposed to respond to the economic value of mining by reducing liability from metallurgical waste.

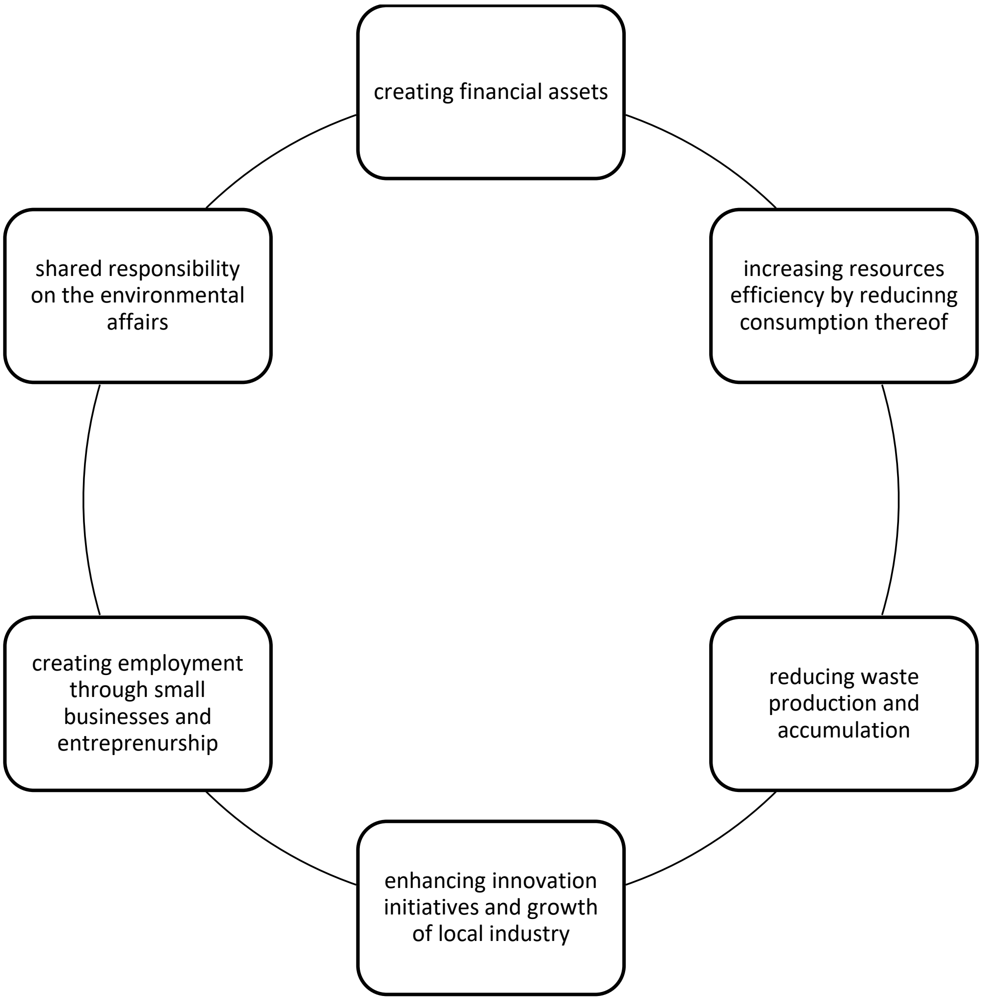

Figure 1. Some of the short- and long-term benefits of recycling and reusing metallurgical waste.

2. The Circular Economy to Improve Mining Waste Management

In this section, we start by looking at the overall mining and metallurgical waste management framework. The lawmakers have made strides in delivering social awareness programs focusing on environmental laws to mitigate the anticipated threats of mining waste (Table 1). Environmental and social regulations' primary purpose is to enhance the protection of communities around the mines and the environment while promoting ethical conduct for businesses [5]. The laws are ineffective when comparing the amount of waste generated and disposed of by the mining companies. However, there are policies meant to regulate the disposal of metallurgical waste [12,13]. Most of these environmental policies emphasize the rights of compatriots to a clean environment that enhances social and economic growth. Some environmental policies from different countries are summarized in Table 2, for example, regulations from SA, USA, and EU.

The design of a circular economy has three fundamental principles: to eliminate waste and pollution, circulate products and materials at their highest value, and regenerate nature. As such, the mining sector seeks many solutions to eliminate pollution through circulating waste and byproducts from metallurgical processing, hoping to produce valuable products, i.e., for construction. As much as the circular economy is considered for economic, environmental, technological, and social improvements, this has yet to be fully realized by all countries, especially emerging economies. (Figure 2 and Table 2).

Table 2. Waste management regulations in different countries.

South Africa	
National Water Act (no. 36 of 1998)	It gives guidelines for mine water management to prevent pollution, water reclamation and reuse, discharge, and treatment. (Department of Water and Environmental Affairs, 2010).
National Environmental Management Act (no. 107 of 1008)	It gives guidelines and boundaries for sustainable development and highlights the duty of care and mitigation strategies to minimize environmental risks. It further states the legal authority to enforce environmental laws and prosecution/liability for the lack thereof. (Department of Water and Environmental Affairs, 2010).
Minerals Act (no. 50 of 1990)	It gives a broad framework for enforcing environmental protection and management. It also stresses the importance of environmental rehabilitation.
Air Quality Act (no. 39 of 2004)	Specifies the need for controlling air emissions of dust using green technologies and clean production practices to protect humans and the environment.
U.S.A. (Environmental Protection Agency, 2015)	
Clean Air Act (1970)	It gives guidelines for airborne pollution, which has the potential to harm humans and the environment.
National Environmental Policy Act (1970)	Compels environmental impact assessments (EIAs) for all economic activities that may pose environmental hazards. Further states that specifically, mining activities EIAs, need federal approval.
Resource Conservation and Recovery Act	The framework of conserving natural resources while reducing the generation of waste. Furthermore, it talks about waste management principles to protect the environment in different categories.
Comprehensive Environmental Response, Compensation and Liability Act (1980)	Guidelines on reporting chemical handling and releasing hazardous substances to the environment compel users to rehabilitate the site where hazardous substances are disposed of, including mining, milling, and smelter waste.
European Union (European Commission, 2010 and 2015)	
European commission on mining, metallurgical and industrial processes	Water framework directive for the protection of groundwater sources; Environmental assessment directive; Industrial emissions directive—focus on remediation strategies for waste management in various industries; Developing a waste management plan for minimization and recovery.

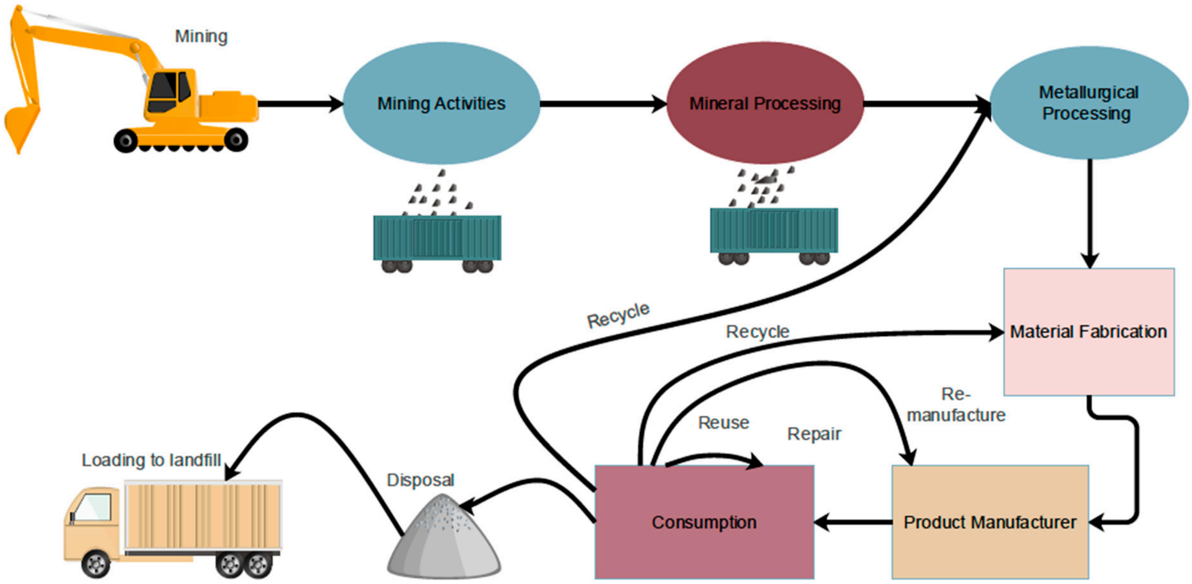

Figure 2. Mining activities with material flow.

Over recent years, the mining and metallurgy industry made strides toward an operational circular economy concept [14], defined as a way of thinking about the sustainable economy [15]. Mining processing occurs outside the CE model; reprocessing metallurgical waste to recover other minerals is referred to as primary extraction. This is particularly strange, as the recycling of the materials, by design, is meant to occur within the CE cycle. An overview of the Ellen MacArthur Foundation [16] illustrates in Figure 2, the material flow, which shows the exclusion of the reprocessing operation in the CE cycle.

As such, there should be a way of re-zoning the reprocessing of waste as a focus on industry economics. This suggestion is supported by Stahel [17], who describes a CE as part of industrial strategies for waste prevention, resource efficiency, and labor. Stahel [17] further advocates for selling or outsourcing instead of owning the generated waste as a sustainable business model for a CE, which sees the business profiting by externalizing risks and costs attached to waste.

The fundamental of the CE concept and its application to economic systems and industrial processes has improved to incorporate different features and contributions from a variety of concepts that share the same ideas as an integral part of the circular economy; the concept of sustainability must be considered. Sustainability must have an element of the transformation of human behavior that enhances living conditions, supporting their health and security [18]. As cited earlier, the research by Ellen MacArthur Foundation [16,19] has paved a pathway for collaborative efforts for business, academia, and policymakers.

3. Treatment Options Analysis

While mining is necessary and has many positive economic benefits, the vast amount of mining and metallurgical sector processes are often accompanied by the generation of large quantities of mine waste [20,21]. The mine waste can contain high levels of metallic and metalloid contaminants that can be highly harmful or toxic to the environment, land, and plants, including biodiversity [7,22,23]. In many parts of the world, including South Africa, many environmental and health risk challenges for communities are directly linked to mining waste practices and management strategies [20,24]. The significant steps of mine processes, including the extraction of ore, refining, and processing of mineral resources, will recover valuable minerals from mine ore and generate significant amounts of waste. Typically consisting of overburden, waste rock, tailings, slags, dust, mine water, sludge, and other waste materials [25]. Air pollution, for instance, due to dust emissions from the extraction and processing of ores, leads to the severity of greenhouse gas emissions, which has a profound impact on acid rain effects and deforestation [26,27].

The large volumes of mining waste generated from mining processes cannot be outright discarded but must be strategically managed to meet the demands for increasingly sustainable environmental practices and primarily for improved individual or community well-being [28,29]. In some places, environmental hazards and damages to the surrounding areas could be far more significant than the mining site due to various mining processes and operations. Therefore, the environmental and safety standards of mining should be continuously maintained [30–32]. Therefore, the effective treatment of mine waste in mining processes is highly critical. In addition, the technological-based strategies and management of mining waste should be targeted to the mitigation of environmental and health-related challenges from these mining processes [7,33,34].

3.1. Reclamation

The contemporary and technologically advanced strategies in mining may result in the recovery of various minerals from large volumes of waste generated [35,36]. At the center of the problem, mining companies still need help with the best waste management from various mining processes and operations. For instance, the detrimental effects from tailings, open-pit mine wastewater, mineral processing wastewater, and wastewater from various laundry activities, particularly in hazardous mining sites, also affect rivers or river streams, soil, wildlife habitats, and the quality of life in the local communities living near these mine sites [22,37].

Reclamation is a process of modifying or restoring the mined area post-mining operations. The environmental rehabilitation of the mining-affected sites should essentially form part of economic and environmental standards. Environmental rehabilitation should be able to restore altered soil properties or profiles in these mining sites, produce water quality that meets human needs, and produce desired long-term land characteristics [38–40]. The rehabilitation process includes the minimization of soil erosion, dust generation, water pollution, and other various factors in these mine sites [21,41,42]. Contaminated land due to accumulated heavy metal substances in reclaimed mining sites soil can enter the food chain through crop plants. These can also accumulate in the human body through biomagnification [43–45]. Therefore, contaminated land remains the biggest threat to human health and ecosystems. Restoration of vegetation and reforestation applied in mine waste or low-grade mine soil will mitigate environmental pollution in soil and preserve wildlife. However, the reclamation application remains not fully appreciated or implemented globally in every mining company or industry, especially in underdeveloped countries, because it is highly resource-intensive. Realigning and implementing active mining laws and regulations should be central to reclamation management and environmental rehabilitation.

For effective implementation of reclamation, a thorough assessment of soil structure, quality, and soil mineral content quality and concentration of the levels of minerals in the mine site is essential [46,47]. With the presence of metals in the soil and the acidic nature of the mining site to be rehabilitated, one of the simple and cost-effective techniques involves adjusting the soil contents by adding lime reagents or other contents with the potential of neutralizing the acidity of the topsoil structure. The process becomes vital in the altered soil characteristics to promote and enhance vegetation growth. The other advantage is stabilizing soil materials and preventing surface water infiltration and soil erosion in these mining sites [48,49]. In addition, agriculture mining technology is also gaining heightened interest in mitigating the issue of mining waste minerals. This emerging technology involves planting excessive amounts of hyperaccumulator plants. These plants are capable and have the potential to extract metals from mineral waste soil by absorbing and accumulating toxic heavy metal substances from the soil. The toxic metals in soil are of great interest in environmental rehabilitation because they can enter the food chain and ultimately accumulate in the human body [50,51].

3.2. The Mine Wastewater and Treatment Options

The wastewater from mining or mineral processing activities is a very useful or valuable resource for overcoming water shortages and demands from mining activities. The nature of mine wastewater, particularly its quality and the level of pollutants, can be highly variable due to various mining operations and practices adopted. The mining water source can be highly contaminated due to byproducts, metalloids, metals, and other pollutants from mining activities. The number of toxic contaminants may have various effects on the environment and human beings [33,52,53]. Each wastewater source will have a different level of the amounts of pollutants and nature of pollutants. A thorough understanding and assessment of any water reuse or end-use forms the more significant part of the thorough assessment of water quality analysis. If not treated, the mine wastewater pollutants can end up in several large water bodies, such as dams, groundwater, rivers, or river streams. They can even harm the environment and human beings in the nearby mining environment [54,55]. The significant sources of mining water include mineral processing water, alkaline water, acid rock or mine drainage, and residual waters. Statistically, the mining water from mining activities accounts for the most significant proportion of mining operations. In most instances, these may originate from open pit mine wastewater, mineral processing wastewater, and wastewater from various laundry activities.

3.3. Different Treatment Options

To date, different treatment options for mining or metallurgical wastewater exist, and the selection and use of a specific technology should consider many considerations. In addition, a specific selection of the preferred water treatment technology strongly correlates with its ultimate or intended end-use purpose [25,56,57]. Most importantly, the water quality, costs, water flow or capacity, and ultimate water end-use must be considered when selecting any preferred water treatment technology. Mine water treatment techniques and technologies for mine wastewater can be classified as chemically, physically, biologically, and physio-chemically and ecologically specific [58,59]. These water treatment methods may also be classified as active, passive, or in-situ treatments based on a wide range of specific applications, construction, and operational mechanisms.

The active treatment technologies for mine wastewater primarily depend on continuous human intervention or interaction for their effectiveness and operational mechanisms. For effective performance, these treatment technologies also require maintenance and monitoring. The most common treatment technologies include neutralization, metal precipitation, membrane processes, removal of heavy metals, ion exchange, and biological sulfate. By its design, each emerging technology is unique, including its application in a specific type of application and performance in water treatment. In underdeveloped communities, passive treatment technologies can be more valuable and cost-effective if utilized adequately. They do not require continuous human interventions in operation or maintenance and often require lower costs due to the gravity flow mechanism's advantage in water movement. Constructed wetlands, aerobic or anaerobic wetlands, anoxic or open limestone drains, and reducing and alkalinity-producing systems are some of the technologies for passive treatments [60,61]. Most importantly, combined with existing or modern predictive modeling tools are now one of the options in using these technologies for mine wastewater; these technologies can significantly complement the analytical methods and computation data analysis and minimize time factor analysis at the cost of accuracy.

3.4. Acid or Coal Mine Drainage Control and Treatment

Acid mine drainage (AMD) refers to the outflow of acidic water from coal or metal mines. AMD is the most significant environmental problem in most active or abandoned mine operations. It affects aquatic ecosystems when mine waste containing sulfate material, such as pyrite or iron sulfide, is exposed to water and oxygen. A high-acidity solution is produced in the presence of a high concentration of heavy metals and fine sediment or precipitate [44,62,63]. However, acid mine drainage sources can also vary the color of the water stream due to mine-affected location and time factor, that is, orange or red-colored water depending on the concentration of the metals in the water. The level of coal mine drainage in water is directly linked to the presence of aluminum, iron, manganese, and other pollutants in various concentrations. It may have different hardness levels, sulfates, and silica [64,65].

The acid or coal mine drainage must be either cleaned or treated (prevent and remediate) to remove the high concentration of metals using appropriate and cost-effective treatment technology. Similarly, large-scale passive treatment, such as anoxic limestone drains, constructed wetlands, anaerobic sulfate-reducing bioreactors, open limestone channels, or active treatments technologies of mine wastewater are commonly used to treat and control metal-rich contaminants in acid or coal mine drainage. The direct treatment method of mine water with the neutralization process, such as lime treatment, is one of the effective options in adjusting and controlling the acidity of water. As such, the increase in the pH of water results in the precipitation of the dissolved metals [66,67]. The abandoned mine sites are also a significant source of AMD, and adding lime materials or waste lime in these mines will no doubt be one of the effective strategies for dealing with AMD formation. Alkaline materials are often used for importation, resulting in the prevention of AMD formation [68]. Disposal of mine waste underwater, bacteria control, and relocation are some treatment options for mitigating acid mine drainage in mining water [57,69]. Fast-tracking cost-effective AMD treatment technologies, especially in underdeveloped countries, still require urgent attention.

3.5. Tailings Disposal and Treatment Options

Reprocessing of minerals in tailings could offer various economic and environmental benefits. Tailings typically contain many waste materials from the extraction of targeted minerals, and more tailings are produced worldwide [70,71]. The characteristics of tailings in terms of the level of contamination and the amounts of pollutants largely depend on the type of processed ore and mining processes used. Tailings can contain a high concentration of metallic elements, sulfides and oxides, carbonates, silicates, process fluids, and other minerals [72]. Therefore, these toxic pollutants in mine-produced tailings are a serious source of concern in mine waste due to the toxic effects that can be produced on the environment and society. Following processing, tailings are either discharged on the ground, pumped as slurry, thickened as a paste or for a greater density and transported to storage facilities for deposition. In standard practices, tailings are stored in storage facilities, such as tailing dams, underground, and rivers and, in some instances, dried before finally being discharged [73,74]. In the past and to some degree today, rivers or oceans were commonly used to dispose of mine waste tailings due to the absence or lack of enforcement of stringent environmental mining laws and regulations in mining industries.

As described in Table 1, large volumes of mine waste are stored as wet tailings in mine tailings storages or discharged into tailing dams. The advantage of this is that tailing dams can be retreated or reprocessed to recover some of the minerals in them, and the reclaimed water can be pumped to the plant environment for reuse purposes [75]. Although no single or specific design for tailings could be universally adopted, each design should aim to protect the environment, human health, and communities while being responsibly managed. The processing of mine waste tailings from the plant environment is usually carried out using thickeners and, in some instances, with the aid of specific polymer reagents [76]. As part of effective water management, the water recovered from the thickener through overflowing channels is pumped back to the plant as reclaimed water. These various filtration techniques are used to filtrate and retain solid materials, including horizontal belt filters, vacuum disc filters, centrifuges, horizontal plate filters, and filter presses. These techniques save space for the required storage facility, compared to storing a wet tailing slurry after disposal [77].

Backfilling technique is commonly used to dispose of mine tailings, reducing surface environmental effects by storing it underground. With many tailings dam failures over the past decades, it is one of the preferred methods, perhaps because it is more beneficial to support the mine infrastructure. An alternative option includes dry stacking of a thickener underflow tailing, which involves the transportation of tailings to the filtration plant to perform the filtration process. The resulting filter cake is transported out of the filtration plant for stacking [78]. Desulfurized tailings can be used in construction cement materials or road construction materials, or even sustainable building products. The increased application is gaining significance in various industries, where the metals in cobalt, nickel, copper, manganese, and magnesium can be recycled or recovered from these tailings. The remaining product can then have various applications in industries, including the construction of eco-friendly building materials or as a cement substitute or replacement product [70,79,80].

4. Products Recovery, Recycling, and Reuse Options

4.1. Construction Materials

Mining operations produce many solid byproducts, such as mine tailings (MTs), which are the solid residues left over after valuable minerals have been extracted from the ores. Many studies have focused on tailings as a better way to increase the utilization of industrial byproducts to alleviate disposal issues, and some byproducts can be used in construction [81–83]. Large amounts of mine tailings are produced and disposed of at high monetary, environmental, and ecological costs. Furthermore, quarrying for natural construction materials is costly and harmful to the environment; many areas lack natural construction materials. The MTs present an opportunity to be explored while finding ways to deal with the dilemma. The mine tailings can be used as substitute construction material to recycle waste products, especially in hollow blocks, bricks production, paving stones, and floor tiles. They can also be used in the production of roller compacted concrete (RCC), cement mixtures, and paint production as a filler. Many studies have shown their potential in cement and concrete mixtures [84–86]. Table 3 shows the results of the cementitious characteristics from the recovered mine waste.

Table 3. Properties of mine waste recovered as construction material.

Originality of Waste	Recycled/ Recovered Material	Porosity (%)	Concrete Density (kg/m^3)	Compressive Strength (Mpa)	Flexural Strength (Mpa)	Tensile Strength (Mpa)	Mixing Rate (%)	References
Gold mine waste rock	building concrete	-	-	36	-	-	100%	[87]
	gravel	-	-	40	-	-	100%	[87]
	cement concrete	-	-	37.8	-	-	100%	[88]
Mine tailings	sand in cement concrete	26.4–29.3		8.58–10.9			100%	[89]
Tailings (copper mine)	sand in cement concrete		2243.53	approx. 40	approx. 4.7		20%	[90]
			2281.34	approx. 38	approx. 4.5		40%	
			2306.54	approx. 36	approx. 4.4		60%	
Tailings Phosphate mine waste rock	cement	approx. 35.5		approx. 29.5			10%	[91]
	cement	-	-	13.5	1.3	2.65	100%	[92]
	concrete		2360	29	4.9	2.6	100%	[93]

These MTs are treated as wastes that require technologies for their disposal through landfilling after reaching maximum capacity. When it reaches its maximum capacity, it will require reclamation. The use of tailings as construction materials can be an option to pursue to achieve the zero-waste strategy. The difficulties associated with tailings storage are increasing. As technology advances, lower-grade ores can be mined, resulting in larger volumes of waste that must be safely stored. Environmental regulations are also evolving, imposing more stringent requirements on the mining industry, particularly in tailings storage [7,94,95]. This puts additional strain on tailings facility operators, who are responsible for tailings discharge and water management daily [96,97]. Nowadays, the production of construction materials is the primary reclamation of mine waste and tailings. Significant amounts of disposable or recyclable byproducts are generated by industrial processes, posing waste management issues [98,99]. Tailings are also disposed of in large quantities by mining and mineral processing operations on occasion. Their management should be undertaken with the goal of producing new products while reducing the carbon footprint on the environment. Mining tailings can be used for a variety of purposes, including backfilling operations and improving the strength and durability of concrete. Tailings can be classified into coarser and finer sizes due to the variation in grain fineness in different mineral processing plants. For most mines, coarse tailings can be used as fine aggregate in concrete, while fine tailings can be used to make bricks. Through the recycle, reuse, and reduce strategy, tailings have many positive environmental impacts.

4.2. The Mine Tailing-Based Geopolymers

The use of mine tailings (MTs) as aggregates or precursors of alkali-activated materials and geopolymers (GPs) is a recommendable approach. It allows for reducing MTs accumulation in the environment and environmental damage. Furthermore, the reduction of the carbon footprint related to the use of geopolymer technology and the ability to use other technologically generated aluminosilicate wastes are considered advantages [53,100–102]. Considering the complex material composition of mine tailings, as well as the relatively little knowledge of the features of tailings geo-polymerization and the influence of various factors on the properties of MT-based geopolymers, there is now a need to generalize these aspects and assess the prospects for potential applications. Binder pastes, mortars, and concretes based on MTs can be used, as well as bricks, backfill materials, adsorbents, porous materials, and other promising applications. Their inclusion in these products may influence production costs, making them more affordable. As a result, MT-based geopolymers can be useful in the construction industry; however, characterization is required to define the content of the MTs to decide on the appropriate applications [103–105].

Nonetheless, it is observed in Table 4 that the building bricks produced from various mine wastes were improving their mechanical and physical properties with the increase in firing temperatures. Noticeably, the results obtained from fired bricks are promising since the increased temperatures influence the decrease in toxicity of the produced bricks [106]. In theory, the toxicity should decrease, but no studies have measured the toxicity levels before and after the firing process. This finding is a knowledge gap that needs urgent attention in research. Furthermore, the firing process of the bricks requires high temperatures, which results in an energy-intensive process; this is an area where researchers need to establish if the benefit of the process outweighs the energy utilization.

Table 4. Characteristics of bricks from mine waste (adapted from Ally et al. [106]).

Waste Type	Drying/Firing Conditions	Compressive Strength (Mpa)	Flexural Strength (Mpa)	Shrinkage (%)	Porosity (%)	Water Absorption (%)	Density (g/cm^3)	Reference
Fe tailings >80%	12 h air drying Firing at 900 °C, 950 °C and 1000 °C for 2 h at a rate of 120 °C/h	6 to 27	-	0.9–1.2	27 to 34	15.5–17.5	approx. 2	[107]
Phosphate mining waste	24 h air drying Firing at 900 °C, 1000 °C and 1100 °C for 2 h	-	17–36	approx. 3.4	7 to 22	3 to 17	approx. 2.6	[108]
Mine tailings	24 h air drying Firing at 900 °C, 1000 °C and 1100 °C for 5 h at a rate of 48 °C/h	-	3.5–11.8	1 to 8	22–42	12 to 26	approx. 1.9	[109]
Phosphate sludge >99%	24 h air drying Firing at 950 °C 1000 °C, and 1100 °C for 3 h at rate of 120 °C/h	-	3.9–13.4	5.2–7.5	9 to 13	12.5–17.2	approx. 1.3	[110]
Coal dust/ powder	Firing from 950 °C to 1100 °C for 2 to 4 h at a rate of 300 °C/h	8.5–17.5	-	-	-	14–18	approx. 1.74	[111]

4.3. Backfilling Mine Cavities

Tailings and waste rocks from mines could also be used in a mined backfill area; both open pit and underground mines can do so. Tailings can be buried in previously excavated voids. Tailings are usually combined with a binder, usually cement, and pumped underground to fill voids and support an underground mine [75,112,113]. The cemented backfill acts as a support, preventing problems with heading collapse and subsidence. On the surface, backfill tailings are typically mixed with cement before being piped down a decline, shaft, or surface borehole(s) into the mine. Backfilling is one of the zero-impact strategies for making use of tailings and waste rocks. It has the advantage of reducing land usage while also reducing environmental pollution [75,77,112,113]. With the advancement of backfilling technology, more and more industrial solid waste, such as tailings, waste rock, and smelter waste, could be used as backfill materials. It is critical for a mine transitioning from open-pit to underground to pay close attention to backfilling technology for solid waste disposal. In an underground mine, backfilling the mined-out area could prevent ground subsidence effectively and reduce the destruction of land [114,115]. When the filling method is used in underground mining, the solid waste discharge could be drastically reduced. Backfilling the opencast in a mine transitioning from open-pit to underground mining can improve stress distribution on the opencast side while also preventing rainwater from entering the underground mine. Backfilling the opencast in a mine transitioning from open-pit to underground mining can improve stress distribution while also preventing rainwater from entering the underground mine. Backfilling should be completed to prevent contamination of groundwater. Prior to backfilling, an environmental assessment may be recommended to ensure the option's long-term viability, in comparison to other tailings management options. Because tailings are fine-grained, they can fill the gaps between waste rocks, increasing the amount of solid waste used. Meanwhile, it may increase the density of backfill materials while decreasing their coefficient of permeability.

Backfill has the benefit of providing stability or support to the mine, lowering the risk of rock bursts, improving the ventilation circuit in the mine, and preventing roof falls caused by blasting. Furthermore, the binders help to reduce groundwater contamination. Backfilling, however, is expensive if binders are used. When using or performing backfilling, tailings must usually be highly dewatered to a paste consistency. Tailings effluent could seep into groundwater, potentially contaminating it.

4.4. Mining Rock Waste

Mining waste, such as coal mine waste rock used in road embankments, has produced acceptable granulometry properties. Amrani et al. [116] found that coal mine waste rocks possess similar quality parameters, such as hardness, compared to gravel. This material is suitable for the construction of pavements and compatible with road works guide and may also be used as foundation material. Furthermore, Amrani et al. [116] tested phosphate mine waste rock and observed that it might be used as foundation material since it achieved more than 95% dry density, as stated in the road works guide (Table 5). Even though the characteristics of the mining waste, such as grading, hardness, and wear resistance, are comparable to that of road materials, they need to be used with much caution because there is a possibility of leaching, thus causing soil contamination.

Table 5. Quality results of the mine waste used in road construction.

Waste	CBR		Standard Compaction		Modified Compaction		
Characteristic	**CBR 4i%**	**IBI %**	**W_{opt} %**	**Pd_{opt} (kN/m^3)**	**W_{opt} %**	**Pd_{opt} (kN/m^3)**	**Health Risks/ Hazards**
Phosphate mine waste rock	13	-	12.9–14.60	17.9	-	-	Possibility of leaching
Coal mine waste rock	9	29	11.2	19	10.11	20.4	Possibility of leaching

CBR—California bearing ratio used as a measure of strength in the subgrade of roads or paving.

5. Health Implications in the Recycled Construction Materials from Mine Waste

As much as the environmental impacts associated with mine waste are significantly reduced with recycling efforts to make new construction materials, the human health of the end users of these materials should also be prioritized. The human health threats could be initiated by air inhalation or ingestion from leachate and dust that can be exacerbated by the mine waste recycled construction material exposure to different weather conditions [117]. Cohen Hubal et al. [118] raised concern with children due to the increased possibility of exposure, thus increasing the chances of ingestion. Some researchers reported possible health effects in structures built with construction material recycled from metallurgical waste [119,120], such as the inhalation of dust. Table 6 demonstrates the correlation coefficients for the concentration of selected elements from recycled mine waste bricks. The Hg element showed the highest rho of 0.617 in floor samples which is a health concern. McEwen et al. [120] assert that researchers in this field need to observe indoor quality and exposure levels and propose mitigation solutions to reduce the exposure in households.

Furthermore, according to the risk assessment model employed in this investigation, Table 7 indicates that the proportion of homes with reported amounts of Hg, As, or Pb exceeded a health benchmark. Even though the study focused on children, it still calls for concern about where the mine waste construction material is used. Health and risk assessments must be carried out on all materials proposed to be reused in households.

Table 6. Rank correlation coefficients (rho) for elements' concentrations in mine waste bricks.

Metal	Dust on Bricks	Dust on the Floor	Surface Dust
n	42	48	41
As	0.572	0.298	0.308
Ag	0.528	0.17	0.3
Cu	0.46	0.161	0.046
Hg	0.617	0.453	0.636
Pb	0.264	0.082	0.098
Zn	0.133	0.079	0.05

Table 7. Toxicological reported values for concerning metals (Adapted from McEwen [120]).

Element	RfD	Major Health Effect	Other Health Concerns	References
As	0.3	Vascular complications	Kidney disease, gastrointestinal, neurological	[121]
Hg	0.3	Autoimmune	Liver, hypertension, gastrointestinal, neurological	[122]
Pb	0.6	Decrease in IQ	Heart disease, gastrointestinal, neurological	[123]

6. Future Possibilities Benefiting the Circular Economy within the Mining Sector

There is a persistent environmental concern with enormous amounts of solid waste products generated by mining and metallurgical operations. A proposal fit for a circular economy strategy, considering the lessened impact on the environment, could be recycling and reuse of these solid waste products instead of using natural raw materials which are already at depletion levels. For instance, the volarization of metallurgical waste slurry as construction material decreases the demand for the natural raw material, whilst, offsetting the price of building materials. Numerous researchers have highlighted a noticeable price upward trend for sand because of the overuse thus depletion of natural sand and gravel which are the essential materials in the creation of building concrete [124,125].

As part of the recycling strategies, the metallurgical waste, whether hazardous or non-hazardous, can go through an immobilization process. In a case where the waste is non-hazardous, it may be mixed with other solid waste which has binding properties for the prevention of pollutants leaching. However, it is important to note that hazard identification and health studies on toxicity levels are needed to confirm the health impact of these recovery construction materials. Upon completion of the process, different construction materials may be produced, such as concrete or bricks. In addition, it may be important for each country to check its construction products regulations, if it includes a provision on the sustainable use of natural resources, where applicable, can include the use of recycled materials, as suggested in this paper.

Moreover, there is a possibility to further extend the circular economy drive through the metal recovery of some valuable metals, such as iron (Fe), from the mine solid waste, as proposed in Figure 3. It is important to note that, following such a proposal, there is a need for an extensive cost factor analysis to ensure that the process indeed fits within the scope of the circular economy.

Another recovery process could be from the drum separator through the improvement of the leaching technology which may result in titanium dioxide (TiO2) and/or aluminum (Al) recovery, depending on the metal content of the metallurgical waste (Figure 4). The process could be reasonably cost-friendly due to a less energy-demanding process. Just like any other process, a proper design and optimization study is required to ensure recovery efficiencies offset the disposal costs. Moreover, additional costs for reagents and solvents need to be considered mainly for the leaching process. The proposed processes in Figures 3 and 4 uses a hybrid approach of physical and chemical metallurgy. With a chemical approach, cost-effectiveness and eco-efficiencies is enhanced. Table 8 shows the advantages and disadvantages of the existing techniques of metal recovery from metallurgical waste streams.

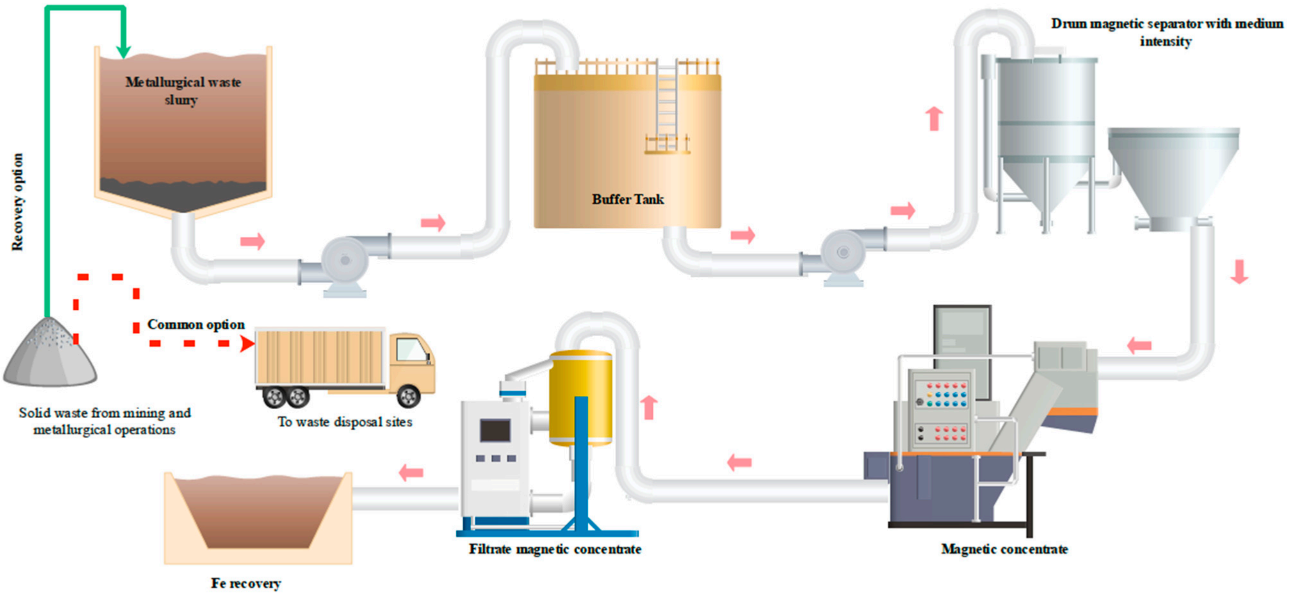

Figure 3. Metal iron recovery system from metallurgical solid waste.

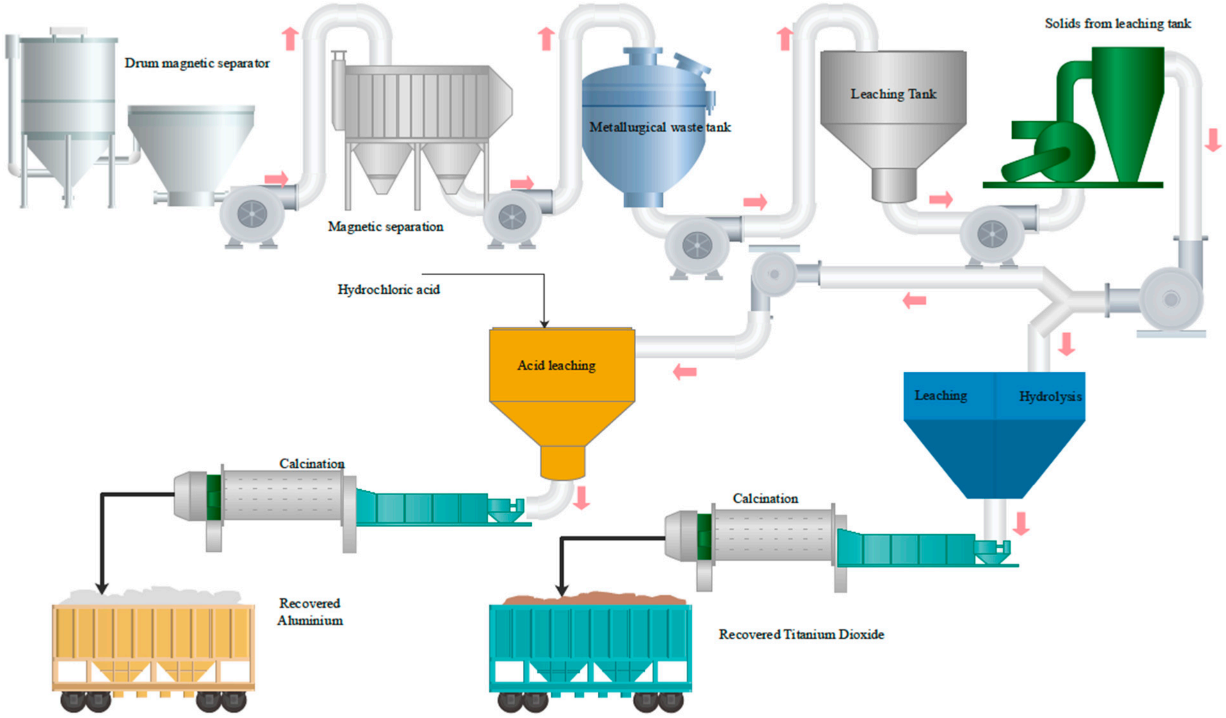

Figure 4. A possible hydrometallurgy process for the volarization of mine waste.

Finally, implementing the circular economy concept to mining waste presents a significant opportunity to reduce liability while increasing mining waste value. However, there are still many challenges, which include current regulatory policies and public acceptance of these mining waste-derived products. Some solutions to these challenges are mainly related to socioeconomic aspects, engineering, environmental, and metallurgical processes, and mining laws and policies. Through circular economy, the mining industry and regulators will be able to carry out full-scale projects, including final residual wastes, utilizing natural cycles and transformations of metals in the environment, and most importantly, creating resilience to resource cycles, for example, better responses to changes in the global supply and demand for various resources [7].

Table 8. A glance at the successes and drawbacks of the process techniques for metal recovery.

Technical Process Technique	Metal Recovered by the Process	Advantages of the Process Technique	Drawbacks of the Process Technique	References
Hydrometallurgy	Al, Fe, Ti, cryolite	Novel technique for the recovery of cryolite	Other elements in the waste stream are inhibited	[126,127]
Hydrometallurgy	Gallium	Efficient Ga by resin	Other elements and metals in the waste stream are not considered	[128]
Combined strategy	Al, Fe, Ti	Fe and Na_2SO_4 recovered	Other elements are not considered in the process	[129]
Combined strategy	Ti, and Fe	Economical and precipitation process is excellent	Other elements are not considered due to pyrometallurgy dominance in the process	[130]
Mineral beneficiation	-	Proved to be carbon efficient and economical	Concentrate magnetic and non-magnetic fraction	[131]
Current proposal	TiO_2, Fe	Physical separation	Design and start-up	Proposal in this paper
(Hybrid approach)		Hydrometallurgy Chemical metallurgy	may be expensive	

The fast-tracking of cost-effective AMD treatment technologies remains an urgent priority, particularly in developing countries. Furthermore, the level and extent of AMD treatment technology's optimal performance, availability, and maturity play a significant role in AMD treatment decision-making. Other factors to consider when selecting an AMD treatment technology include the acid mine water quality source, the concentration amounts of contaminants in water, water chemistry, water volume, and quantity, and geological factors [59,132,133]. Because the specific technology for the intended application will have financial implications, the fitness criteria and scope for the purpose must be carefully chosen. In practice, short- and long-term financial viability should be considered to achieve successful and feasible AMD treatment decisions. As a result, cost-effective AMD treatment in terms of maintenance and operational costs should also be considered [133].

Moreover, the circular economy may assist in social security at a specific level that satisfies the minimum human needs for health, security, housing, information, and social protection, including employment [134]. There is a need for research in these areas for the CE model to be completed and implemented. As illustrated by Markevych et al. [135] in Figure 5, all components of economic security need to be considered for the CE model to align with economic security. All green blocks in Figure 5 demonstrate how the recycling of mine waste contributes to the CE model, and all red blocks highlight a need for further research to realize the end goal of economic security. The amber colors represent the areas partly tackled by the recycling/recovery activities of metallurgical waste into construction materials.

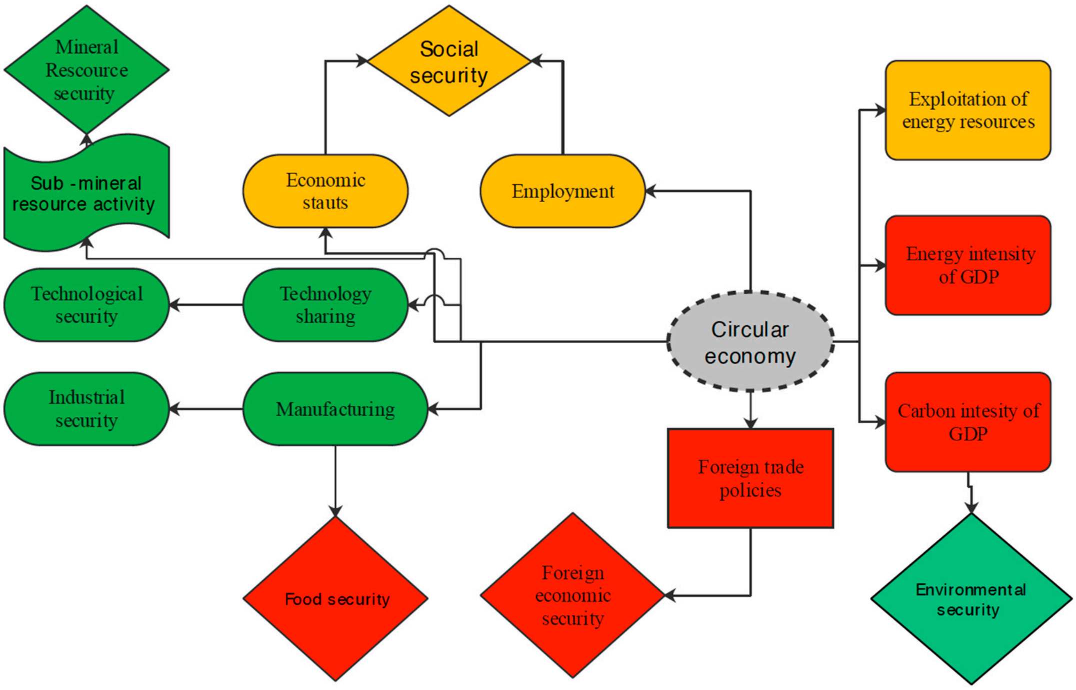

Figure 5. Connection between the circular economy and the facets of economic security (adapted in Markevych et al. [135]).

7. Conclusions

Even though it has been determined by Markevych et al. [135] that the circular economy concept combines the peculiarities of various system-forming economic security components, the paper focused on the environmental and industrial facets. This paper discussed different options available for possible ways to improve the reuse and recovery of metallurgical waste using an inclusive circular economy model. More research is still needed to merge metallurgical waste onto the ecological system, including social and food security. As part of cost-cutting measures, mining sites should design a systematic control of metallurgical waste through hydro-technical systems, and then recycling, and reprocessing initiatives. Without a doubt, the reuse of metallurgical waste in the production of various building materials is the most notable measure to keep the environment from being adversely impacted. Moreover, there is an opportunity of offsetting the cost of metallurgical waste storing and/or transporting to disposal sites, by reusing the waste to manufacture building materials. However, as much as manufacturing building materials from metallurgical waste is meaningful, these materials are potentially harmful to human health and the environment. As such, the manufacturing process and practical application of these building materials must be under stringent ecological surveillance, and more studies on the toxicity levels are needed. Furthermore, a study on the perspectives of the end users of these recovery materials will be of interest to the researchers in the field. For these reasons, new technological strategies need to be developed to improve the quality of the by-products, such as building materials, to make them more attractive to consumers, which in turn will increase their commercialization. Lastly, whilst the mining industry is subjected to strict regulations, which include social and environmental consciousness, the issues of sustainable development and the incorporation of the CE model within the business are critical.

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