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Review

Technospheric Mining of Mine Wastes: A Review of Applications and Challenges

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Abstract: The concept of mining or extracting valuable metals and minerals from technospheric stocks is referred to as technospheric mining. As potential secondary sources of valuable materials, mining these technospheric stocks can offer solutions to minimise the waste for final disposal and augment metals' or minerals' supply, and to abate environmental legacies brought by minerals' extraction. Indeed, waste streams produced by the mining and mineral processing industry can cause long-term negative environmental legacies if not managed properly. There are thus strong incentives/drivers for the mining industry to recover and repurpose mine and mineral wastes since they contain valuable metals and materials that can generate different applications and new products. In this paper, technospheric mining of mine wastes and its application are reviewed, and the challenges that technospheric mining is facing as a newly suggested concept are presented. Unification of standards and policies on mine wastes and tailings as part of governance, along with the importance of research and development, data management, and effective communication between the industry and academia, are identified as necessary to progress technospheric mining to the next level. This review attempts to link technospheric mining to the promotion of environmental sustainability practices in the mining industry by incorporating green technology, sustainable chemistry, and eco-efficiency. We argue that developing environmentally friendly processes and green technology can ensure positive legacies from the mining industry. By presenting specific examples of the mine wastes, we show how the valuable metals or minerals they contain can be recovered using various metallurgical and mineral processing techniques to close the loop on waste in favour of a circular economy.

Keywords: technospheric mining; mine wastes; green technology; eco-efficiency; circular economy

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1. Introduction

Technospheric mining refers to the extraction or recovery of metals and minerals from the technosphere, a stock or accumulation of materials generated by human activities and technological processes. In contrast to conventional mining, which targets primary ores of geologic origin, technospheric mining is geared towards valorisation of wastes and waste repositories [1]. It is considered as an important step towards the circular economy and sustainable development in the mining industry. The goal of technospheric mining in the mining industry is to acknowledge mining wastes as technospheric stocks, to add value to wastes through reprocessing, resource recovery, or repurposing, to reduce the amount of final waste for disposal, to ensure minimal environmental impacts, and to provide additional socioeconomic benefits to all stakeholders [2].

The extractive nature of the mining industry poses environmental impacts and create negative mining legacies that need to be reversed, reduced, or mitigated. According to a recent OECD report [3], environmental legacies can vary depending on mining practices and impact ranges. Different management approaches are required to address the distinctive legacies of different mining practices and impact ranges. Amongst many of the key challenges that the mining industry faces, the generation and management of mine wastes have the potential to create a long-term environmental legacy [4–7]. A significant amount of waste is being generated at various stages of mining operations from exploration, mineral processing, and metal extraction. Mining wastes are unwanted, currently uneconomic, solid and liquid materials found at or near mine or processing sites [4]. Examples include waste rocks, overburden, tailing, metallurgical slag, process residues, and waste effluents [8,9]. These wastes create significant on-site storage problems and pose human and environmental risks due to dust generation and potential release of heavy and toxic metals they contain.

However, mine wastes are also considered a veritable treasure trove of some critical, strategic, and rare metals and other materials [10–14], which when recovered, can help augment the global demand. Aside from metal recovery, the mineral matrices contained in mine wastes have been utilised as repurposed materials for construction [15,16], geopolymers [17,18], phosphorus removal from wastewater [19], and CO_2 capture [20,21]. Sustainable ways to store, manage, reuse, or reprocess these wastes are indispensable to make mining more eco-efficient and optimise its social and economic benefits. These regenerative aims constitute the main premise of technospheric mining in the mining industry.

This paper reviews technospheric mining as a new paradigm with a particular focus on wastes generated by the mining industry and identifies candidate technospheric stocks out of these mine wastes. This work aims to contribute to addressing the knowledge gap around recognising mine wastes as valuable technospheric stocks. The physical, chemical, and mineralogical characteristics of mining wastes targeted in studies are described. A review of studies, applications, and emerging technologies relevant to metal and mineral recovery as part of technospheric mining is presented. This paper also discusses how technospheric mining is linked to concepts relevant to environmental sustainability, eco-efficiency, green technology, resource conservation, and the circular economy in the mining industry. The key criteria, drivers, major players, and challenges for technospheric mining are also reported. The authors attempt to take an intergenerational and interdisciplinary perspective that extends beyond the immediate or short-term notions of waste repurposing and understanding of material flows in the lithosphere through technospheric mining.

2. Technosphere

The term 'technosphere' was introduced in the late 1990s [22–24] as a suggested new component of the Earth along with the biosphere, atmosphere, hydrosphere, and lithosphere. The technosphere refers to a material stock that has been generated by human activity and is currently excluded from the material flow [1]. The components of the technosphere include urban infrastructures, agriculture, marine landscapes, and even air. Non-physical components such as carbon dioxide, methane, oxygen, and other pollutant gases from human activities can also be regarded as part of the technosphere including aerosols, dusts, and other particulate matters suspended in the air, which are eventually rained out and become part of the ground and other technospheric components. The technosphere as an emerging paradigm shares similar properties with the natural spheres, such as the lithosphere, atmosphere, and biosphere, according to P.K. Haff (2013) [25], in the sense that is also has a global coverage and involves systems including the appropriation of resources, CONVERSION of resources and structures, recycling of resources, and autonomy [25,26]. An estimate in 2017 indicated that the technosphere is comprised of 30 trillion tonnes of different materials and components [27].

Table 1 shows the different features and classification of the technosphere as suggested by Johansson et al. [1]. In-use, hibernation, dissipation, tailing, slag, and landfill technospheres were identified. This classification was based on a copper (Cu) and iron (Fe) inventory as these metals are prevalent and used in a multitude of applications, and covers location, size, concentration of minerals or metals, management status, and activity state. In-use stocks are materials that are currently being used, including operational equipment and appliances, buildings, and infrastructure; these usually contain high concentrations of metals. These stocks have no management options and can only be accessed or utilised for reprocessing or recycling at their end-of-life service. Hibernation stocks refer to end-of-life products or materials that are not managed or controlled and are awaiting further processing or disposal. Examples of these stocks are abandoned ships in shipyards, or waste electrical appliances in the backyard. Dissipation stocks are usually small in terms of volume and can contain low concentrations of metals or materials. Dissipation can include dust particulates, aerosols, and airborne pollutants that are distributed to the atmosphere or the ground either from gas emissions, ground water seepage, leaks, or other uncontrolled material transport mechanisms. These stocks are normally handled for environmental abatement or decontamination rather than resource recovery [1,9].

Table 1. Features of the technosphere (primarily relevant to copper and iron) [1].

Technosphere	Location	Relative Size	Concentration	Management	State
In-use	Urban	Large	High	-	Active
Hibernation	Urban	Small	High	Uncontrolled	Inactive
Dissipation	Rural	Small	Low	Uncontrolled	Inactive
Tailings	Rural	Medium	Average	Controlled	Inactive
Slag	Rural	Small	Average	Controlled	Inactive
Landfill	Fringe	Medium	Average	Controlled	Inactive

A number of these features are highly relevant to the mining industry, particularly tailings and slag, which can be considered significant components of the technosphere [28]. These stocks, including landfill, are more accessible and are normally controlled by companies that produce them or government agencies, and in some cases, exploited as a secondary resource [9,29,30]. Tailings and mine waste can include overburden, or waste by-products of mineral beneficiation or extraction processes. These stocks are normally in the medium-to-large category in terms of size but may contain significant amounts of recoverable metals or minerals. Tailings can be classified as either active (produced by current operation) or historical (tailings storage facility). Some tailings from historical operations when extraction and processing technologies were not yet sophisticated may contain valuable metals of concentrations even higher than primary ore sources. Slag is a by-product or waste material generated by high temperature metallurgical processing or pyrometallurgical processing of ores or mineral concentrates. Processing of Cu and nickel (Ni) sulphide minerals, iron ore, and tin minerals, particularly cassiterite (SnO_2), produces slag materials. Slag may contain critical and strategic elements, such as cobalt (Co), rare earth elements (REEs), and refractory metals, such as titanium (Ti), tantalum (Ta), and niobium (Nb) [31,32]. Landfills are inactive stocks that contain mostly municipal solid waste and other industrial rejects. This technospheric stock can be available for resource recovery but the challenge is that it is highly heterogeneous and existing metals are disorganised. The current focus for mining landfills is more on composition mapping and identification, along with finding appropriate excavation technology [1].

As discussed above, wastes generated by the mining industry, such as tailings and other by-products, are significant components or features of the technosphere. Mine wastes are one of the world's largest waste streams and often contain high concentrations of elements and compounds that can pose risks to the environment and humans [4]. These wastes and waste repositories have great potential as secondary sources of valuable metals, materials, and minerals. Reprocessing, repurposing, or recycling these mine wastes as part of technospheric mining would not only add value to these wastes but would also provide a solution to the storage and disposal problem. Millions of tonnes of ore are processed every year by the mining industry, >95% of which is disposed of in the form of waste rock and mine tailings [13], with enormous tracts of land used to store or dispose of this. Utilising mine waste and tailings as secondary sources of metals and minerals for future processing can ensure resource conservation and minimise the environmental burden caused by mining activities.

While several multidisciplinary pieces of research on mine waste and tailings are available, most of them focus on characterisation, stability, impact, or remediation. Reuse, reprocessing, or repurposing of tailings and mine waste is another aspect that has been gaining global attention recently. This approach is covered by technospheric mining (or mining the technosphere), an important new concept that is considered to provide a holistic solution to managing historic, contemporary, and future waste from the mining industry [1,4,33,34]. A review of the studies and current practice of technospheric mining concepts is presented in the next section.

3. Technospheric Mining

Technospheric mining is a relatively new concept that refers to the extraction and recovery of metals and mineral stocks from the technosphere stocks that have been generated by anthropogenic activities and accumulated in different forms in the lithosphere. This concept of 'mining the technosphere' was introduced and elaborately discussed by researchers from Sweden, Johansson et al. [1] and Krook and Baas [33]. The researchers developed the umbrella category of the technosphere and technospheric mining concepts (shown in Table 1) based on the source, size, concentration, and the controls or management options available. The publication by Johansson et al. [1] was the first review technospheric mining and is now considered the foundational text of the new concept.

A schematic diagram (Figure 1) of how the different features of technospheric mining can be integrated in a material flow from mineral processing to product manufacturing was introduced by Binnemans et al. [9]. Each stage of the flowsheet generates wastes or byproducts that need to be managed or controlled. The management approaches for these wastes encompass technospheric mining concepts. For instance, processing primary ores to produce a concentrate would generate tailings that can be dealt with by mining either to reprocess them and recover valuable metals or to repurpose them for different applications. Product manufacturing yields metal scraps that can be directly recycled or reprocessed through urban mining. End-of-life products can go to landfill (to be mined/reprocessed through landfill mining in the future) or can be sorted and recycled through urban mining options. The processes to recover value from each stock vary depending on the type, source, composition, mineralogy, and other factors. Hence, Figure 1 may evolve depending on the conditions and characteristics of the technosphere.

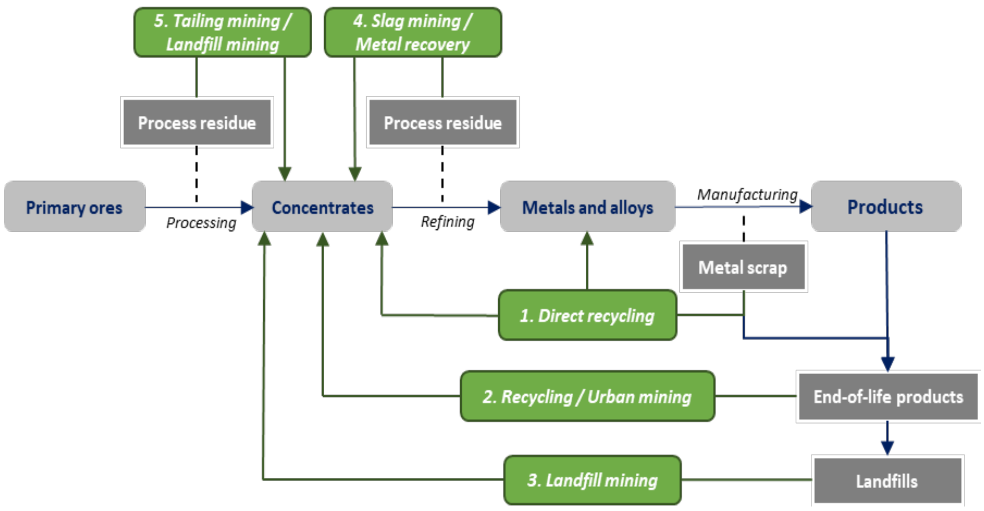

Figure 1. Technospheric mining of mining wastes (adapted from Binnemans et al. [9]).

The term 'technosphere' is the brainchild of USA scientist Peter Haff [25] and was introduced in the late 1990s, though it was only quite recently that the notion of mining the technosphere (or technospheric mining) came to be known through the paper published by Johansson et al. [1] in 2012. The paper described technospheric mining as a new taxonomy with the aim of consolidating definitions and other concepts related to recovery and recycling of human-generated stocks. Soon after, Krook and Baas [33] reported the feasibility of landfill mining and urban mining from the umbrella scheme of technospheric mining and identified a resilience model with important dimensions, such as metabolic flows, business, governance, and infrastructure, as well as market strategies. Nowadays, increased interest in the use of the terminology has been observed with a number of research studies published highlighting its application [9,27,35,36]. This has resulted in advancing technological development for technospheric mining, especially of mine wastes [34,37]. So far, conceptual, social science, geological, and technological aspects of technospheric mining and the technosphere have been reported. This review provides potential applications of technospheric mining in the mineral industry, particularly in the areas of metallurgy, mineral processing, and mining, and attempts to integrate and emphasise environmental sustainability in the concept.

Technospheric mining incorporates recycling concepts and is coherent with the circular economy approach and sustainable development goals. The primary focus of technospheric mining is metal and mineral recovery and it encompasses all possible sources and forms (urban, rural, and dissipated) [1]. A fundamental difference between technospheric mining and conventional recycling or similar concepts is that the definition of material stocks (referred to as technospheric stocks) for technospheric mining is comprehensive and concrete, with an effort to include all streams in the material cycle [1]. The benefit of having a broad definition of material stocks is to maximise the utilisation of all stock streams in technology development and eventually processing. The initiatives and technologies from other recycling concepts are still supportive of sustainable development, but lack the focus and essence of closing the loop of the material cycle.

The motivations of technospheric mining are to valorise wastes, i.e., the wastes generated by the resources industry, and minimise the environmental burden of storage and disposal. Waste valorisation of mine wastes will not only add value to these waste streams and afford environmental benefits to stakeholders but will also promote resource conservation of metals and mineral resources. For example, the amount of Cu in tailings storage facilities (TSF) around the world is estimated to be about 0.13 gigatonnes, which is equivalent to about 15% of the current geogenic copper reserves [38,39]. Reprocessing these copper tailings through technospheric mining would preserve our primary copper sources and promote resource efficiency. This would also contribute significantly to environmental sustainability for various reasons: (1) minimise the impacts of excavations brought by conventional or virgin mining, (2) reduce the amount of final waste for impoundment or storage, (3) minimise contamination from dusts and seepage of toxic and heavy metals associated with mine wastes, and (4) improve safety and stability of tailings dam and storage facilities due to reductions in volume and capacity [4,39,40].

Resource recovery from technospheric stocks, particularly from mine wastes, can offer several benefits relevant to operational and technical aspects. As opposed to traditional mining or mining of minerals from geological origins, extraction of metals or recovery of materials from some mining wastes would not require excavation, intensive comminution, ot size liberation stages since the feed material has already undergone the grinding process, which contributes to a significant reduction of investment, operating cost, and carbon footprint [1,8,9,21,33]. Resource recovery from these waste streams can be divided into two main categories as shown in Figure 2: (1) metal recovery and (2) material recovery. Metal recovery involves reprocessing mine wastes and extracting valuable metals not considered worth extracting in the initial process, either by physical or chemical methods. The main target of this category is to recover metals of value. Material recovery, on the other hand, consists of separating or extracting compounds or minerals for repurposing applications. These categories are dependent on the physical and chemical composition of the waste, the type of mining, and the method used to process the mineral [13]. Each category is discussed and reviewed in the succeeding sections.

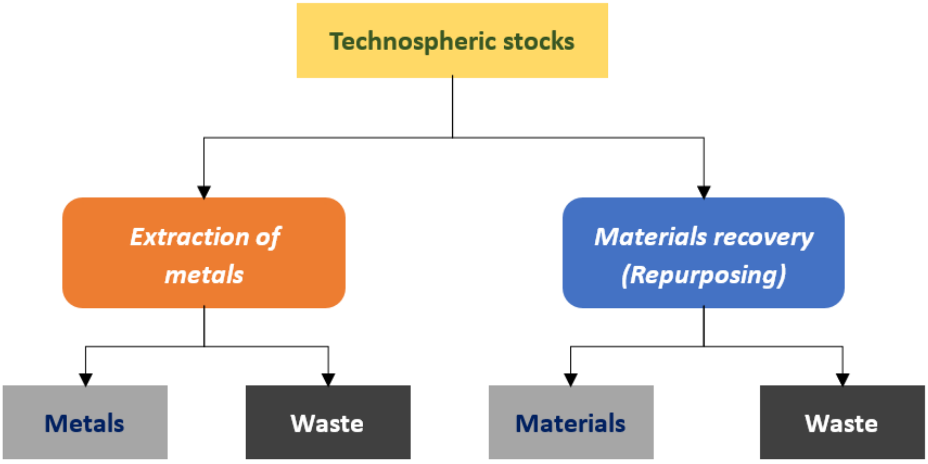

Figure 2. Metal and material recovery flow of technospheric stocks.

3.1. Metal Recovery

Mine wastes may contain various metallic elements either from associated gangue minerals or residual target minerals that have not been separated properly due to process or technology limitations. Some mine waste or tailings may contain valuable metals, such as rare earth elements, precious metals, or critical and strategic metals, that were not considered worth extracting when the ores were initially processed, but are now considered highly valuable due to increasing demand and newly found applications [9,11,13,41,42]. A summary of the mine waste, tailing, and process residue containing valuable metals is shown in Table 2. One of the notable observations from this list is that the valuable elements in the stocks are not necessarily from their primary ore deposits. For example, tin (Sn) slag (by-product of tin ore pyrometallurgical processing) may contain significant amounts of refractory metals, such as Nb and Ta [14,43]. Copper tailings and slag, as well as nickel slag, may contain Co, which is an important element of battery manufacturing [32,44,45]. These technospheric stocks can be considered important secondary sources of rare and critical metals that are essential for the economy and industries. The following subsections present some examples of technospheric stocks from the mining industry that are targeted at metal recovery, along with the technologies that are used or emerging. Mining wastes, such as metallurgical by-products, are materials that underwent treatment, either through mineral processing and separation methods (crushing, grinding, size-sorting, flotation, and other physico-chemical techniques) or extraction methods (leaching or smelting). Compared to mining and processing primary ores, reprocessing mining wastes could significantly lower mining costs, as the material is already crushed, ground, and treated [46,47].

Table 2. Valuable elements that can be recovered from technospheric stocks from the mining industry.

Stocks	Samples	Metals	Sources
Tailing	Copper tailing	Cu, REEs, Co, Ni, and manganese (Mn)	[41,45]
	Tungsten tailing	Tungsten (W), molybdenum (Mo), and Mn	[48]
	Iron tailing	REEs and Fe	[49–51]
	Lead-zinc tailing	Fe, silver (Ag), gallium (Ga), lead (Pb), and Mn	[52]
Slag	Copper slag	Cu, Co, Ni, Ti, vanadium (V), and chromium (Cr)	[32]
	Nickel slag	Ni, Co, and Ti	[31]
	Tin slag	Nb, Ta, Ti, and Sn	[43]
Residue	Nickel laterite	Ni, Co, Cr, and Mn	[53]
	Bauxite residue	REEs, Ti, and Sc	[10,34]
Fly ash	Nickel laterite	Ni, Co, Cr, and Mn	[54]
	Coal powder	Ti, Mn, and magnesium (Mg)	[55]

3.1.1. Hydrometallurgical Residue

Hydrometallurgical residues are solid by-products of leaching or aqueous processing of ores or concentrates to extract target metals. One of the hydrometallurgical residues targeted as an important technospheric stock is bauxite residue, otherwise known as red mud [12]. Bauxite residue is a by-product of the Bayer process of aluminium production and contains valuable elements, such as scandium (Sc), REEs, and Ti, that are crucial for the future battery industry [10,56]. Scandium is present in bauxite ore in low concentrations, but during the Bayer process, is concentrated to as much as double its original concentration. Sc is a rare earth element that has found wide applications in aluminium (Al) alloy production [56]. The contents of Sc in bauxite residue vary depending on the source but can range from 40 to 1000 mg/kg [57]. Every ton of aluminium produced generates 1 to 1.5 tonnes of bauxite residue. More than 2.7 billion tonnes of bauxite residue have been stockpiled so far, and every year, 150 million tonnes are being added to this inventory [12,42]. Only 3~5% of bauxite residue, at the moment, is being repurposed for cement and ceramic production [19]. This presents the immense potential for bauxite residue as a valuable source of Sc.

Understanding the sample's mineralogy and characteristics is crucial to developing suitable and efficient technology for the recovery of Sc from bauxite residue. Bauxite residue is highly alkaline with a pH range of 10~13 and can contain around 7% silica that can potentially cause silica gelation, complicating the handling and solid-liquid separation [10]. A typical chemical composition of bauxite residue consists of 6.9~23.6 wt.% Al_2O_3, 6.8~42.5 wt.% Fe_2O_3, 3.0~23.8 wt.% SiO_2, 2.5~17.9 wt.% TiO_2, 1.8~46 wt.% CaO, and 1.6~12.4 wt.% Na_2O [12]. The main mineral phases present in bauxite residue are gibbsite ($Al(OH)_3$) and boehmite (γ-AlO(OH)) for aluminium, hematite (Fe_2O_3) and goethite (FeO(OH)) for iron, quartz (SiO_2) and kaolinite ($Al_2Si_2O_5(OH)_4$) for silica, and rutile/anatase (TiO_2) for titanium [12,58]. The composition can vary depending on the source, process, and geological background. Bauxite residue can also exhibit electrical conductivity due to a high content of sodium (Na^+) and high pulp density. Naturally occurring radioactive materials such as uranium (U) and/or thorium (Th) can be present in bauxite residue [58].

The speciation and association of Sc in bauxite affect its concentration in the residue and dictate its extraction process. Gentzmann et al. [56] reported three factors that significantly contribute to the presence of Sc in bauxite residue: (1) bauxite ore type (karstic or lateritic), (2) oxidising and reducing process, and (3) the dominant species of Sc in the bauxite ore. Karstic bauxites contain carbonate rocks that stabilise Sc at an alkaline pH and prevent Sc from being extracted during the process. Thus, karstic bauxite residues tend to contain a higher content of Sc than lateritic bauxites, though only 11.5% of the bauxite reserve in the world is karstic. Meanwhile, 88% of the reserve is lateritic bauxite and the other 0.5% is the Tikhvin type. Karstic bauxite reserves were discovered in Europe, Jamaica, and China, and lateritic bauxite reserves were found globally, especially in Australia, South America, West Africa, and India [59]. The difference between karstic and lateritic bauxites can be determined based on the geology, texture, mineralogy, and geochemical features. The major Al-phases of lateritic bauxites are gibbsite (Al $(OH)_3$), boehmite, and diaspore (AlO(OH)). Karstic bauxite can be distinguished when the main Al mineral is boehmite and the major Ti component is anatase. Also, karstic bauxites occur in karst cavities [60,61].

The chemical condition in the Bayer process also determines the concentration of Sc in the residue. Oxidising conditions traps Sc into the crystal lattice of Fe phases such as goethite and hematite, which are hardly affected by the Bayer process. On the other hand, the reducing process mobilises Sc onto clay minerals, which can be dissolved during the Bayer process and interfere with the transfer of Sc to bauxite residue. Sc in bauxite residue is also associated with minor phases, such as rutile, anatase, and ilmenite, though the minor minerals only exist in small concentrations. Identifying how Sc is associated with various components and mineral phases in bauxite residue, either adsorbed or incorporated, is essential for extraction technology development, but it is an area that still requires further study and understanding [56].

Several methods have been identified and reported to extract valuable elements, particularly Sc, from bauxite residue. These include acid or alkali leaching, bioleaching, carbonisation, and some pyrometallurgical pre-treatment methods [12,34,57,62–64]. Reid et al. [34] recognised the potential of technospheric mining for bauxite residue to recover REEs, such as Sc and neodymium (Nd), employing microwave pre-treatment followed by leaching with sulphuric acid. In microwave pre-treatment, dielectric heating vaporises water molecules in the sample and creates nano-sized pores, which allows the reagent to diffuse further and increases the leaching efficiency. After the treatment, 10–20 nm pores were created, which significantly increased the porosity of bauxite residue. This work highlighted the development of the technology and potential of technospheric mining for bauxite residue, especially in relation to mineral processing [34]. Among the many methods reported, carbonisation has been identified to have great potential for further development since this method not only dissolves scandium but also reduces the toxicity of bauxite residue through neutralisation [64], a great example of the green technology needed for technospheric mining. Opportunities to improve leaching recovery with this method, such as mechanical activation and ultrasonic treatment for carbonate leaching, were mentioned. Once the carbonate leaching reaches its maximum potential, testing and adapting carbon dioxide for carbon capture and utilisation (CCU) technology can be considered [65].

3.1.2. Pyrometallurgical By-Products

Pyrometallurgical processes generate various slag by-products. These wastes from high-temperature extraction processes can be classified mainly into two categories—namely ferrous slag and non-ferrous slag—according to their origin and characteristics. Many slags are produced annually around the world and are mostly disposed of in dumps. Slags usually contain significant amounts of valuable metals and are considered as secondary sources of metals [29,37,66]. Shen and Forssberg [30] published a review paper on the recovery of metals from slag and described different metals that can be recovered from ferrous and non-ferrous slags. Metals such as Fe, Cu, Al, Ni, Co, Nb, Ta, Ag, and gold (Au) can be recovered from slags using mineral processing techniques (crushing, grinding, magnetic separation, flotation, leaching, or roasting). These non-ferrous slags are now considered important technospheric stocks for critical and strategic metals.

In the copper smelting process, copper-rich matte and impurities in the molten state are separated by adding flux (silica) and combining oxides strongly with silica to form an iron silicate slag. Lime and alumina in the flux stabilise the slag. The cooling methods applied to the slag determine the physical characteristics of the slag. Slow cooling forms a crystalline product, while fast cooling by water quenching forms a granulated amorphous slag. About 95% of copper slag is made up of oxide components, and the major phases include fayalite ($2FeO \cdot SiO_2$), magnetite (Fe_3O_4), and augite ($Ca(Fe, Mg)(SiO_3)_2$) [67].

The tin smelting process also generates non-ferrous slag. In the process, Sn is extracted from its primary ore cassiterite (SnO_2), while other elements associated with the ore, such as Ta, Nb, Ti, zircon (Zr), REEs, Si, Fe, Al, and Ca concentrate in the slag [14]. Tin smelting is common in countries like Indonesia, China, etc. Sn processing for low-grade complex ores comprises crushing, roasting, and smelting with a reverberatory furnace, followed by smelting slag for further Sn recovery [68,69]. The smelting process is featured in Figure 3. Tin slag typically consists of 1.1~24.9 wt.% $(Ta, Nb)_2O_5$, 1.3~17.8 wt.% TiO_2, 0.5~8.4 wt.% ZrO_2, 0.1~1.6 wt.% SnO_2, 4.7~11.2 wt.% Al_2O_3, 11.6~29.2 wt.% CaO, 0.9~27.7 wt.% FeO, 11.9~41.9 wt.% SiO_2, and 0.4~3.7 wt.% MnO. The Ta and Nb phases are contained in the dendritic phase [70]. It was determined from microprobe, factorial, and pseudo-structure analysis of tin slag that there is a strong association with Ta, Nb, U, and lanthanum (La), which are the major valuable elements present in the material [71]. Greenbushes mine in Western Australia produce Ta and Nb from tin slag. The reserve of Ta_2O_5 in 2002 was 223.7 Mt with a 0.022% grade [72].

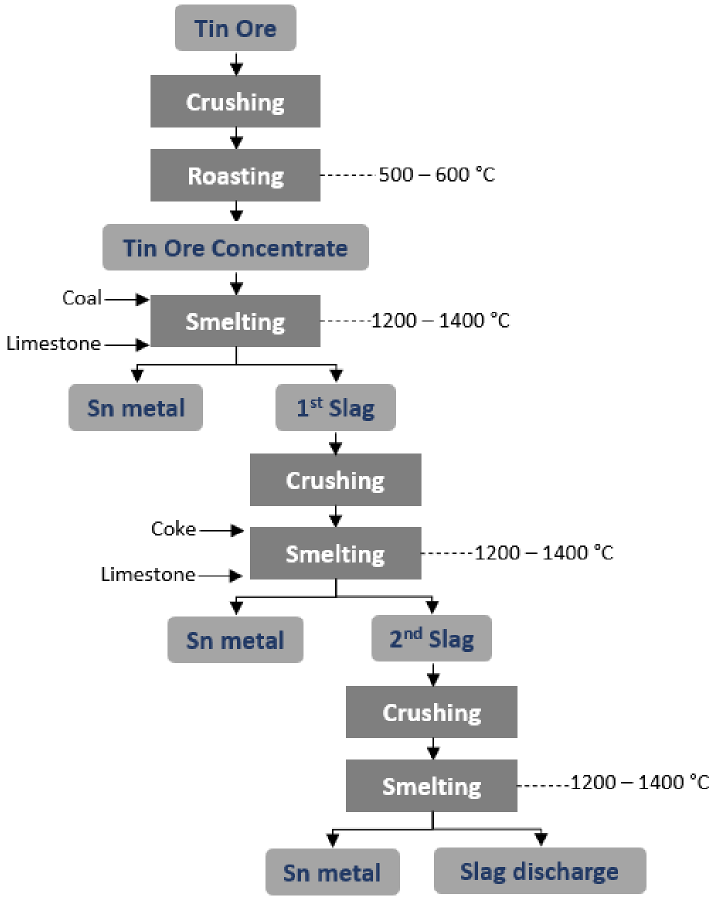

Figure 3. Tin smelting process (adapted from [68,69]).

Among the non-ferrous slags, copper and tin slags are widely investigated for the recovery of Co or Nb and Ta, which are in demand for battery, electronics, and other high-technology applications. The recovery of Co from copper slag from Zambia was studied by Jones et al. [29]. About 20 million tonnes of copper slag containing 0.76% Co was present in dumps in Zambia. A pyrometallurgical process was developed and a furnace was constructed, which recovered 840 tonnes of Co and 100 tonnes of Co-bearing alloy, signifying the feasibility of the process. Nb and Ta recovery from tin slag was also investigated by Gaballah et al. [14] using chlorination (Cl_2-N_2) and carbochlorination (Cl_2-Co-N_2) techniques. The authors were able to completely extract Nb and Ta using the techniques at relatively low temperatures. These studies exemplify the potential of slags as secondary sources of valuable metals; technospheric mining of these slags is not only important for saving metal resources but also for protecting the environment [30].

3.1.3. Mine Tailings

Mine tailings are materials consisting of finely ground rock particles produced during the beneficiation of ores and separation of target minerals. Tailings can be highly reactive due their small particle size and the presence of reactive minerals, like iron sulphides. These wastes may contain high concentrations of base metals and toxic elements, but in some instances, can be regarded as important secondary sources of valuable elements, such as REEs and critical, refractory, and precious metals [13]. Reprocessing tailings (as previously mentioned) can be economical comparing to conventional mining as these materials have undergone comminution and several processing stages already [11,41,73].

Due to the increasing demand for REEs for clean energy and advanced applications, research initiatives and activities on REE extraction and technological development have accelerated recently [9,41,50,74]. Peelman et al. [50] and Tunsu et al. [41] studied the recovery of REEs from iron ore tailings from Sweden, gold and tellurium tailings from Sweden, and tungsten tailings from Portugal, respectively. The iron ore tailings contained about 0.12–0.15% of REEs. The processing plant still produces tailings every year that contain 15 kilotonnes (kt) of REEs on top of 100 kt that have been stored in the tailings dam. The REEs in the tailings were associated with monazite ($REE(PO_4)$) and apatite ($Ca_5(PO_4)_3F$). Beneficiation and upgrading were conducted using flotation. The reprocessing stages consisted of acid leaching, solvent extraction, precipitation, conversion, and calcination and achieved 70–100% REE recoveries [50]. Tunsu et al. [41] investigated the separation of REEs from two tailings sources using solvent extraction and showed that selective separation of REEs from Cu, Fe, and phosphate (P) is feasible.

Mine tailing, other than REEs, may also contain V, Co, Nb, antimony (Sb), and other valuable metals [6,11,46]. Their grades in mine tailings vary depending on the deposits and processing methods. Araya et al. [11] reviewed the processing technology and economic feasibility of the recovery of critical raw materials from inactive copper mine tailings in Antofagasta region, Chile. Two scenarios were evaluated for the production of REEs or vanadium pentoxide (V_2O_5) from the inactive mine tailings. The first scenario of producing REEs with 20 years of mine life can produce USD 670,000 as a net profit value. The second scenario, which evaluates the production of V_2O_5, can generate USD 76 million with 14 years of mine life, a more profitable option than REEs. This review successfully demonstrated a very positive capability of a new business model of producing critical metals from tailings, especially vanadium from Chilean inactive tailings. The findings of these studies are all dependent on many factors including the market price, grade of valuable elements in tailings, amount of stock, and availability of infrastructure, among others.

Aside from REEs and critical metals, mine tailings can also be utilised as secondary sources of other metals, such as Au, Cu, Sn, Fe, and Mn. Carvalho et al. [75] investigated the viability of Au, Cu, Sn, W, and Cu-Pb-Zn tailings from abandoned mines as secondary sources of metals and minerals. Although much work still needs to be done before the option can be commercialised, it was a necessary initial step for tailings mining. Recoveries of Fe from Pb-Zn tailings from China [52], iron ore tailings [49,76], and vanadium tailings [77] have been attempted using magnetising roasting, magnetic separation, and direct reduction processes. Copper tailings can be reprocessed to recover residual Cu; this was demonstrated through studies conducted by Guo-dong and Qing [78] and Kossoff et al. [45].

3.2. Mineral Recovery

Technospheric stocks (i.e., mine wastes) that do not contain metals attractive enough for economic or viable extraction can be diverted and used as sources of materials and compounds that can be repurposed for other applications. A number of these applications are in the building, construction, and production of zeolites and adsorbent materials [6,20,79,80]. Examples of these applications are listed in Table 3. Finding ways to utilise secondary wastes for various applications based on their physical and chemical properties is important. Extending the material cycle of mine wastes is important and is a key feature of technospheric mining [15]. Research and development of the valorisation and repurposing of mine wastes and other technospheric stocks have been gaining a lot of attention recently and several studies have already reported technologies and processes with great potentials [81].

Slags generated by various pyrometallurgical processes, such as electric arc or blast furnace processes, have been utilised as material for construction purposes [15,16] owing to their physical properties [88]. The use of slag in the production of cement, gravel, bricks, mortar, rail ballast, and bridges has also been documented [88]. Slag is rich in alumina-silicate components, which renders the material suitable for such applications. Jarosite, a leaching residue from zinc (Zn) production, can also be utilised in construction after the neutralisation process [89]. Bauxite residue from aluminium processing can be used as an additive in cement, concrete, bricks, and geopolymer production [79]. Recent research showed that carbonate bauxite residue can be suitable as a filter to remove phosphorus from wastewater streams [19] and also as a catalyst [81].

Table 3. Applications of technospheric stocks from the mining industry.

Stocks	Samples	Applications	Sources
Overburden	Waste rocks dumps	Backfill and construction	[6]
	Tungsten mine waste mud	Geopolymeric binder	[82]
Tailing	Gold tailing	Geopolymer	[17]
	Copper tailing	Concrete and brick	[83,84]
	Tungsten tailing	Cement	[85]
	Iron tailing	Sand substitute, production of cement, glass, brick, ceramic, and tile	[86]
Slag	Copper slag	Construction, cement additive, blasting agent, fertiliser, and metal salt	[66,80]
	Nickel slag	Ceramic, cement, and geopolymer	[18,87]
	Tin slag	Road pavement	[88]
Residue	Nickel laterite	Zeolite X (CO_2 capture material)	[20]
	Bauxite residue	Construction, catalysts, adsorbents, and ceramics	[79,81]
	Jarosite residue	Construction	[89]
Fly ash	Nickel laterite	Concrete	[90]
	Coal powder	Geopolymer	[91]

Mine wastes have also found applications in geopolymer preparations. Geopolymers are inorganic alumina-silicate-forming materials that are used in concrete, ceramics, and binder applications [17,92,93]. Slag and tailings that are rich in alumina-silicate components have been reported to be source materials for geopolymer production [17,18,91]. These waste materials can also be repurposed as zeolites, which are used as catalysts and adsorbents [94]. Geopolymer and zeolite syntheses from mine wastes and tailings are already established and have been around for several decades; these employ low temperature activation processes using strongly alkaline solutions (i.e., lime or sodium hydroxide).

Metal and mineral recovery streams in technospheric mining complement each other. The secondary wastes generated by both metal and material recovery can be utilised and processed further to close the loop of the material cycle. Technospheric stocks that contain significant amounts of valuable metals can be processed to extract these metals. After metal extraction, the secondary waste produced may still contain useful materials that warrant recovery for any other application or for repurposing. There is also a possibility that repurposing of technospheric stocks may concentrate certain elements that can be valuable in the wastes; however, repurposing tends to use a whole bulk of stocks for building and construction applications rather than extracting materials.

4. Challenges and Future Perspectives

Technospheric mining, as a relatively new concept, is still in its infancy and is confronted by various technical, social, geopolitical, and economic challenges [1]. These challenges, which are highly relevant to technospheric mining of mine wastes, are presented in this section.

Technospheric mining of mine wastes seems far from the commercialisation stage yet as utilisation of mine tailings in terms of resource recovery is not part of international standards. The Global Industry Standard on Tailings Management [95] was published in 2020 and covers various aspects, such as affected communities, knowledge of tailings, design, construction, operation, monitoring, management, emergency response, recovery in case of failure, and closure [95]. Although reclamation, restoration, and reprocessing were mentioned in the standard, not enough detail was included as the standard focuses mainly on the status of tailings. Consultation indicated that 56% of the respondents expressed concerns regarding the standard not considering the whole lifecycle of tailings, which represents a void in the report [96]. It is proposed that due to a lack of practical applications of tailings as secondary sources of metal and mineral recovery, the international standard did not consider repurposing tailings, or only as one of the options in the post-closure.

The Global Industry Standard has been framed with safety and the environment as the primary aspects of tailings management. It fails to consider the value and importance of resource recovery and the potential of additional economic benefits from extracting valuable metals and minerals from tailings and mine wastes. Revisions to this standard to incorporate approaches for tailings reprocessing, repurposing, and recycling should be conducted. This is important to highlight the important role of technospheric mining in the mining industry.

4.1. Technological Development and Data Management

Several research studies have been reported pertaining to technological development for resource recovery from mine wastes as part of technospheric mining, and these include metal and mineral recovery. They are highlighted in Tables 2 and 3. A range of mineral, metallurgical, and chemical processing techniques have been applied [6,11,37,42,97,98]. Despite these developments, technospheric mining of mine wastes still has limited commercial applications. There may be several reasons for these inadequacies concerning process and technology efficiency and practicality, commitment from mining companies to incorporate mine waste utilisation in the process flowsheet, implementation of green technology, and economics [46,99].

Some of the available technologies for technospheric mining of mine wastes lack efficiency and practicality; they require enormous capital and operational investments and do not guarantee an even marginal profit. Some research initiatives reflect situations that are almost impossible to utilise in the field [99]. These make the option less attractive to investors and mining companies and perhaps contribute to their hesitancy to reprocess and utilise mine waste unless the long mine life is given or the market is less volatile [46]. This may not be true in the case of critical or precious metals, which are currently in demand for high technology and cleaner production applications; these can be expensive, allowing for a high return on investment.

Issues related to knowledge and information gaps were highlighted in a review paper by Sánchez and Hartlieb [100]. These issues cause significant delays, either through miscommunication or lack of communication between academia and industry. These gaps could be because of inefficient management and delivery of available data. Information related to characterisation of tailings and mine wastes, production and generation data, or available metallurgical testing data are important for technological development. Research without considering the parameters, circumstances, and infrastructures of the industry is of theoretical rather than practical use in terms of technology. Although mine sites and mining companies generate a huge amount of valuable data every second, confidentiality requirements prevent mining companies from disclosing or sharing this information, which could hamper the advancement of the sector. How the companies utilise these data could be a major driver to speed up the development of the technology [100].

Jakob et al. [99] suggested some solutions to counteract this problem. Enhanced collaboration between engineers at the field (industry) and researchers (academia) to exchange knowledge and experience, to develop more efficient and practical process technologies for technospheric mining, is essential. Data sharing relevant to stock collection, evaluation, and data management for anthropogenic resources can be expanded to an international level for a holistic approach. Creating an international group of experts for a specific commodity is also suggested, which can be learnt and adopted from the traditional mining industry [99,101]. The authors [99] presented an example where there was an attempt to gather experts in solid wastes in Europe and share brilliant ideas for future processing. Instead, the group of experts identified more drawbacks, such as legal, technical, and organisational problems [99]. The lesson from this experience highlights that inclusion of experts from traditional mining and other sectors outside of research can provide useful insights on how to approach issues at the developing stage from different perspectives.

A thorough consideration of different routes for process development is required for technospheric mining of mine wastes due to variabilities associated with the location, commodity, processes employed to generate them, and a lot of other factors. Generally, there is no template that can fit all types of mine wastes or tailings. Some mine wastes are low-grade stocks and some contain relative high amounts of valuable metals. Other mine wastes are disseminated, while some can be concentrated. This is where research and development plays a very important role as the first step in the technological development cycle. Novel technologies should pass laboratory verifications and this should be well-communicated to stakeholders for further testing, large scale demonstrations, and commercialisation [97]. However, a shortage of experts in processing secondary sources will be one of the factors that will delay the implementation and commercialisation of reprocessing of mine wastes. Incorporating this topic and the underlying concepts early on in university education and training of future metallurgical, chemical, or process engineers is indispensable. Building a strong workforce and equipping them with sound knowledge and understanding of technospheric mining and the importance of reprocessing mine wastes is important for a sustainable and eco-friendly mining industry.

Another challenge for technological development in technospheric mining of mine wastes that we must overcome is how to incorporate green technology in the process design and flowsheet. There is an increasing call for researchers around the world to enhance and embed green technology in processing for cleaner production of materials [73,102–105]. Inevitably, green technology will soon become an integral part of processes and technological development due to the rapidly increasing awareness of sustainability in modern society. Global movements and awareness of environmental sustainability are becoming major drivers for academia and industry to adapt green technology in research and operations, even if this may require some level of investment. As highlighted in Net Zero by 2050 [106] and the Paris Agreement in 2015 [107], society is paying enormous attention to and has great awareness of sustainability as it is evident that environmental issues affect people's lives. Thus, supporting green technology and environmental sustainability is a way to attract or secure strong consumer support and patronage for companies or products. Technospheric mining of mine wastes is no exception. Though the literature has contradictory definitions of green technology, the central premise is to pursue environmentally friendly approaches or processes to safeguard the environment. This initiative of including waste in the material cycle is being actively discussed [6,9,75,108,109]. Aside from contributing to the extension of the cycle of the technosphere, technospheric mining should allow for a small environmental footprint, to make it sustainable and eco-efficient.

Green technology can have various facets. One example can be the adaptation of renewable energy in the processing operation. Renewable energy as a source of electricity is an effective method for achieving a sustainable operation by reducing greenhouse gas emissions. For example, the study of environmental impacts from copper mining in Laos, which was done by remote sensing image analysis and life cycle assessment, revealed that when the gross energy requirement value for the open-pit operation was average, the greenhouse gas emissions were lower than average owing largely to hydroelectricity generation on-site [110]. Another example is the use of benign reagents and processes for metal or mineral extraction and recovery. Bioleaching is an emerging technology and has been actively researched with various sources [51,101,111–114]. Since technospheric stocks tend to contain low-grade profitable elements, utilising bio-heap leaching can be one of the beneficial options with minimal investment. Less dependency on reagents that can be harmful for the environment and society is another suggested approach for green technology. Oraby and Eksteen [115] found that the addition of glycine significantly reduced the concentration of cyanide required in the copper-gold leaching circuit. This technology is now called GlyCat™ and it is close to pilot-plat testing from Mining & Process Solutions for commercialisation. Recent research on deep eutectic solvents (DESs) also provides a great example of a green reagent that can replace mineral acids and organic solvents for cleaner production in processing. Thus, DESs can be utilised in leaching, electrodeposition, solvent extraction, etc., though the kinetics and physico-chemical characteristics of DESs still remain to be discovered further [104].

4.2. Eco-Efficiency

An important component to consider in technospheric mining and development of the technology is eco-efficiency. It was first defined in 1992 [116,117] and can be assessed by the material's lifecycle. The fundamental feature of eco-efficiency is to create more products with fewer resources and less waste and pollution [118]. It is closely related to the circular economy and sustainable development [40,109,119–125]. Finding and understanding ways to incorporate and implement eco-efficiency in technospheric mining is necessary. This section presents some concepts and applications of eco-efficiency in the mining industry that can be adapted for technospheric mining.

The first application is the eco-efficiency portfolio developed by Badische Anilin und Soda Fabrik (BASF), one of the largest chemical companies in the world, based in Germany. This portfolio consists of five major factors in the calculation: energy consumption, material consumption, emissions (air, water, and solid wastes), risk potential, and toxicity potential. This tool was developed by the chemical company and it can be applied to research into and evaluation of the other products and processes [119] that will be useful to validate the sustainability of current and future technology.

An example framed for mineral processing, which can be useful for technospheric mining, was developed by van Berkel [126]. The aims and means of this framework are listed in Table 4. van Berkel [126] proposed that eco-efficiency can be achieved from operational perspectives as well as technical, and these perspectives are dependent on implementation. To be eco-efficient in mineral processing, the processes should aim to be resource-efficient, minimise energy, water usage and greenhouse gas emissions, handle minor and toxic elements, and produce by-products. Among all the means listed, the three powerful factors to boost the efficiency are plant operation, plant design, and processing technology [126]. Nonetheless, these factors are very broad and include various sub-factors to be considered.

Table 4. Aims and means of eco-efficiency framework for mineral processing ([126]).

Aims (Resources Productive Themes)	**Means (Prevention Practices)**
• Resource efficiency • Energy use and greenhouse gas emissions • Water use and impacts • Control of minor elements and toxics • By-product creation	• Process design • Input substitution • Plant improvement • Good housekeeping • Reuse, recycling, and recovery

The eco-efficiency analysis for the mining and mineral industry is summarised in Figure 4. Mining practices and aspects encompass lifecycle assessment from extraction to disposal and recycling, categorised under a cradle-to-grave approach. The environmental profile, on the other hand, is more concerned with extraction to product manufacturing aspects, or the cradle-to-grave approach. A lot of these approaches have changed recently and strong considerations of the environmental profile in disposal and recycling have been recommended and implemented for a more eco-efficient system [119,127].

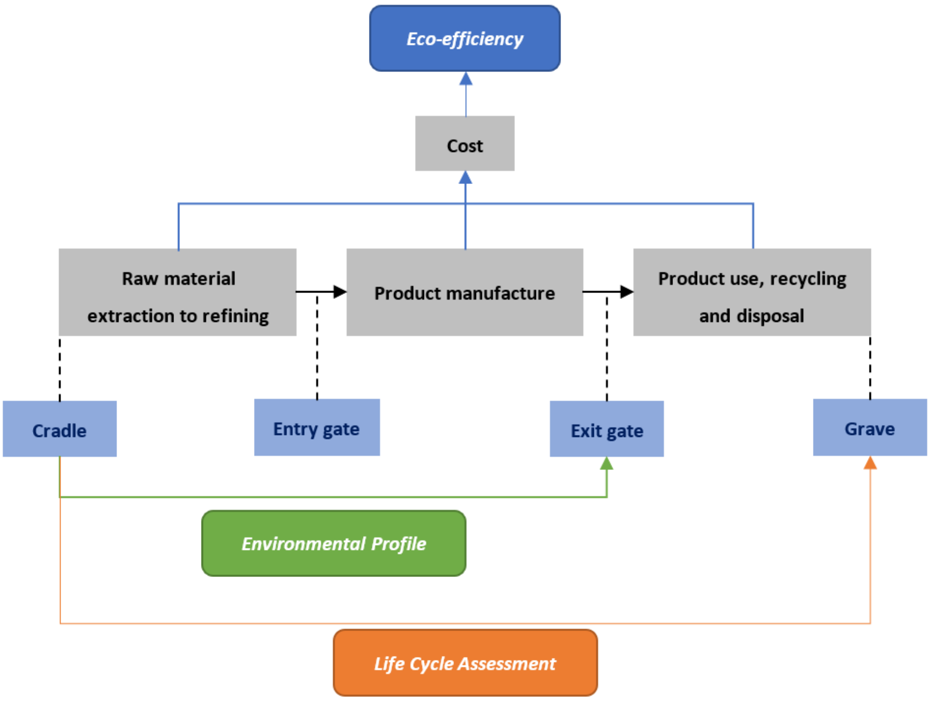

Figure 4. Eco-efficiency analysis for the mining and mineral industry [119,127].

Incorporating green technology and eco-efficiency in technospheric mining is perceived to be a way to achieve environmental sustainability in the mining industry. The economic benefits of green technology may not be as attractive as traditional or other technologies for now but a lot of initiatives have been conducted to improve the efficiency and costs associated with green technology. This can be quite challenging and may take some time to realise, but the environmental benefits of green technology are long-term and encompass different sectors and areas of society.

4.3. Governance

As the concept of technospheric mining is still in its infancy, there have been no uniform, significant government or institutional regulations established as of yet. It was indicated above that the Global Industry Standard on Tailings Management excludes the potential usage of tailings as technospheric stocks. As the awareness of the technosphere in science and society continues to grow considerably, the emergence of a soft law system closely following the legitimate legislative discussions and regulations will be needed to avoid uncertainty [128]. As stated in the literature [46], the proper establishment of regulations is necessary to achieve the circular economy, especially because complex regulations can create a bottleneck in to processes and the wide application of the concept in various sectors of society. Addressing this gap in legislation and governance is extremely important not only for guidance in research and technological development but also for public awareness and support. Some technospheric stocks with high economic value, such as mine waste, tailings, and slag, are likely to be managed and developed by the mining companies, while stocks like hibernation, dissipation, and landfill require more engagement from the government and institutions [33].

Technospheric stocks can be complex and broad due to their multitude of sources and differences in the processes employed to produce them, along with the locations, properties, and other characteristics. Establishing a system to classify them is important to understanding their potential applications and the approaches to reprocessing them under technospheric mining or decontaminating them for environmental purposes. This highly relevant information is indispensable to establishing regulations that are fit-for-purpose.

This can be extremely challenging yet necessary for the sustainable future of the industry and society, and requires interdisciplinary and inter-institutional collaborations.

5. Conclusions

The resources needed in modern life depend on mineral extractions from primary yet limited sources in the Earth's crust. Soon, industry and unmet needs in society will require secondary sources for metals and materials in the interest of sustainability. Once the challenges of developing efficient processes are overcome and technological issues are resolved, mineral wastes can provide a good source of valuable metals from huge amounts of deposits that have been generated by mining practices. Utilising mine wastes as a secondary source will enable the industry to mitigate the negative environmental impacts and legacies that have been created and accumulated since the beginning of mining operations and mineral processing.

Technospheric mining is a concept of extracting mineral resources from the technosphere, which is the material stock that has been generated by anthropogenic activity. In mining, tailings, slag, process residue, etc., are included in the technosphere. Feasible examples of resource recovery from process residue, slag, and tailings have been introduced to recover valuable elements from the technosphere. These examples are important to the viability of adapting mine waste as a secondary source of metals. Studies on process development for technospheric mining are being conducted; however, there is still room to improve the sustainability and efficiency of the extraction process by incorporating green technology and eco-efficiency and moving towards better circularity. Once the technology is developed, several factors such as feasibility testing, market status, accessibility to infrastructure, and social license should be identified to successfully integrate technospheric mining into the business of mining. This paper has argued that technospheric mining has the potential to ease the environmental legacies that have been created by the mining industry. In particular, impacts of the generation and management of mine waste on the environment and society have been identified, with waste management being one of the negative legacies that the mining industry currently needs to address since waste storage facilities have been known to cause disastrous issues if not managed properly.

Technospheric mining acknowledges mine wastes as a technospheric stock from which to extract valuable elements and secure a metal supply, assuring greater conservation of primary sources and the environment. Not only should extraction technologies be feasible and efficient, but green technology and eco-efficiency should also be applied in the development of extraction methods for sustainable development of the mining industry. This study has emphasised mineral processing and reviewed the implications of developing and adapting technospheric mining in line with green technology. Mining the technosphere will contribute to achieving sustainable development by mitigating the environmental legacies of the mining industry. In future research, a greater focus on interdisciplinary collaborations could produce interesting findings that focus more on solving technical issues and developing innovative, feasible, economic, and effective processes for technospheric mining.

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