mining

Review

Use and Recovery of Extractive Waste and Tailings for Sustainable Raw Materials Supply

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Abstract: Extractive waste (EW), including tailings, is produced in large quantities during mining activities. In recent years, the linear economic model ("take-use-and-throw" approach) has been replaced by a circular approach, emphasizing the sustainable use and recovery of EW. The development of innovative protocols, such as Best Available Techniques (BATs), which aim at the technological and process improvement of more sustainable mining activities and at the production of renewable, highly performing green materials, has led to technological advancements, expertise in sustainability, and a reduced ecological footprint, potentially causing positive economic and social impacts and reducing environmental ones. Extractive waste and tailings, if suitably characterized, can be used to improve and make sustainable the works connected to the management of mining activities. The qualitative–quantitative characterization of EW is essential for subsequent reuse and for assessing the risk to human health and the extent of environmental impacts in the various matrices. The application areas vary according to the type of waste and mining tailings, the morphological characteristics of the deposits, and the geological, geomorphological, and logistic context of the area. Integrated protocols for sustainable EW exploitation and positive impacts on the economic, environmental, and technological/social level are analyzed. The present paper aims at providing an overview of challenges and potentialities connected to extractive waste (EW) management and potential exploitation to recover raw materials (RM), critical raw materials (CRM), and secondary raw materials (SRM).

Keywords: sustainable mining; critical raw materials; circular economy; supply chain; waste recovery; recycling

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1. Introduction: Raw Material and Critical Raw Materials Supply

Raw materials (RMs, indicated as feeding goods needed to manufacture products), and critical raw materials (CRMs, "those raw materials which are economically and strategically important for the European economy, but have a high-risk associated with their supply". Def. CRM Alliance—**Critical Raw Materials | CRM Alliance**) were essential in the past as they are nowadays for the sustainable functioning of modern society. They are fundamental both for clean low-carbon technologies [1] and hi-tech, with a consequently more intensive exploitation of metals if compared to fossil-fuel technologies, for example [2]. Metal RMs are normally used in new green technologies for the construction of photovoltaic panel frames, in the structure of wind generators and in the chassis of electric cars. Current examples of using CRM are lithium and cobalt in batteries of electric vehicles, silicon in solar photovoltaic panels, and rare earth elements (REE) in permanent magnets of wind turbines [3].

Thus, it is easy to deduce that the availability of RMs and CRMs will be under greater pressure, which represents a possible bottleneck [4] in the market [5]. Indeed, supply-chain problems with these materials can cause problems in the industrial production of many products, including increased prices and an inability to meet market demand.

The three main indicators to consider when approaching the concept of CRMs (which are critical for EU development) are:

- Supply risks, which are the risks connected to the decreases in the production of most of the industrial sectors (in particular, hi-tech and clean technologies) in case any problem occurs in the supply of feeding materials for industries. A high potential of RMs is still available in Europe, but there is a lot of competition among those who want to explore and extract RMs due to strict environmental regulations and different land uses. CRMs are not widely present in the EU, as they are mainly present and exploited in China, Russia, South Africa, Brazil, and the U.S.
- Economic importance, which is closely linked to their importance for the development of modern technologies, especially in cases where no viable substitution possibilities have yet been found and where CRMs drive innovation. For example, an effective alternative technology to Li–ion batteries for electric cars and e-bikes has not yet been clearly identified [4,6].
- Environmental reliability. When dealing with RM/CRM exploitation, it is fundamental to guarantee the environmental preservation of the particular area from extraction and processing activities (https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en, accessed on the 15 November 2023).

The EU 2023 Study on CRM, which presents the results of the fifth 2023 technical assessment of critical raw materials for the EU, investigated six categories of RMs (industrial and construction minerals, iron and ferro–alloy metals, precious metals, rare earths, other non-ferrous metals, and bio and other materials), stressing the importance of CRMs for the EU. Thirty-four CRM materials in total have been individuates, six more than 2020 (arsenic, feldspar, helium, manganese, copper, and nickel, the last two being strategic raw materials—SRMs), and two individuates were less than 2020 (indium and natural rubber) [7].

The localization of world resources and the main producers of CRMs reveals that Europe is strongly dependent of non-EU Countries, as it is often affected by fluctuating policies of the market [8]. China is the principal producer of 30 CRMs. Several other countries have dominant supplies of specific RMs, such as the U.S. (beryllium), Brazil (niobium), Chile (lithium), South Africa (iridium, platinum, rhodium, and ruthenium), Kazakhstan (phosphorous), Guinea (bauxite), and the DRC (cobalt). For these reasons, together with an increased interest in finding domestic ore deposits for CRM and RM exploitation, there has been a great development of recycling and recovery policy relating to CRMs and RMs (including the chance to recover/recycle extractive waste), in accordance with the transition to a more circular economy that is sustainable, low carbon, resource efficient, and competitive at the same time [9]. Exploiting RMs/CRMs/SRMs from extractive waste (EW) facilities and from EW produced during ongoing mining and quarrying activities is in line with the circular economy principles, which are aimed, thanks to the exploitation of waste as alternative materials to guarantee RM/CRM supply, to:

- Reduce the extraction of natural resources (in line with the EU pillar concerning natural resources preservation).
- Reduce the number and typologies of landfills (including extractive waste facilities).
- Reduce the environmental and human health impacts connected to waste management and landfilling (in line with the EU pillar concerning environmental protection).
- Recover RMs/CRMs from waste (in line with the EU pillar concerning waste recycling).

The needs of the European industry concern not only the CRMs but an extremely wide range of RMs (metals, industrial minerals, and aggregates), such as:

1. **Metals**, in general, are fundamental for industrial development. Fe, for example, is employed in steel production, paint industry, and magnet production; Al (light and resistant) in car and airplane production; Cu (high electric conductivity) is employed for electric devices and line production; Ti (light and resistant) is used in several

applications in airplane production and in medical devices; Au (high conductibility and corrosion resistance) is used not only in the jewelry sector but also in the electrical industry and for airplane windows; Ag (high thermic and electric conductivity) is applied in a range of electrical and electronic applications, including electrical contacts and printed circuit boards, and in medical applications due to its antibacterial properties. Other metals such as **Zn** and **Ni** were and still are crucial for the EU economy (Ni is used for Ni–Cd batteries and in super alloys for electric power stations or for airplane turbines), together with some CRMs, which can be associated to those whose importance has increased over the last decades (e.g., **PGEs** are associated with Ni; Cd, Ge, Ga, and In are associated with Zn–Pb ore deposits). Metals can be exploited from natural ore deposits (still present in the EU countries) and from anthropogenic deposits, such as industrial and urban landfills and extractive waste facilities, which potentially store massive amounts of strategically important materials [10].

2. **Industrial minerals** are crucial for a country's development across various sectors. They have applications in construction (clay for bricks, calcium carbonate for mortars, and gypsum for plasterboard), industries (feldspar, kaolin, and quartz for ceramics and glass), and environmental uses (clay/bentonite as a waterproof material for landfills). Agriculture benefits from minerals like zeolite for soil pH regulation and a slow nutrient release. In animal feeding, calcium carbonate is utilized as food supplement for skeletal and enzyme system support. It has to be highlighted that, principally due to the present fight between Russia and Ukraine, feldspar in 2023 has been included in the list of CRMs. Further to this, feldspar and kaolin can be associated with REE, which could be exploited as an "associated product" of the principal ones.
3. **Aggregates** are very important for the European industry because of their wide application fields, such as:
    - Aggregates for concrete: used in construction, building, and infrastructure sectors.
    - Railway ballast used in railway construction.
    - Bituminous aggregate for road construction.
    - Aggregate for subfloor layers used in railway and road construction.
    - Armour stones and rip rap applied for environmental purposes.

Focusing on RM and CRM needs for industrial development, the present paper aims to provide an overview of challenges and potentialities connected to the supply from ore deposits and anthropogenic ones (landfills and EW facilities), focusing on EW production and EW facilities, which are a potential source of RMs/CRMs and secondary raw materials (SRM) due to their homogeneous characteristics (depending on mine and quarry typologies), which makes them potentially more convenient to exploit, reducing the impacts connected to their management and landfilling.

2. Extractive Waste Production

Mines and quarries have been exploited for many years without a specific waste management policy. This lack of policy has resulted in huge environmental issues connected to waste facilities and waste management in general, such as slope stability, acid mine drainage, water and soil pollution due to metals or chemicals used for mineral processing, etc. (environmental impacts associated with the mining industry are reported in Section 3). Furthermore, an outdated policy regarding mining activity and EW management in general has also resulted in negative social impacts (health problems for local inhabitants, a decrease of land value due to the presence of EW facilities, negative impacts on local traffic due to the transport of tout venants and EW, etc.).

Huge traces of past (and sometimes still present) exploitation activities characterize European countries (dumping areas and EW facilities). More than 4.7-billion tons of mining waste and 1.2-billion tons of tailings are stored all over European Union [11]. More than half of the mining sites within the EU are now closed, with the exception of few metal mines, mines for industrial-mineral exploitation, dimension stones, and aggregate quarries that are still active. EW production represents the second sector for waste production at the EU level, which is characterized by an annual production of about 622-million tons (26.6% of the total amount of waste production) [12]. On a wider scale, about 25-billion tons of EW are produced worldwide each year [13].

The European Directive 2006/21/EC of 15 March, 2006, [14] on the EW management oversees the permit conditions, storage, monitoring, and control of the produced waste to ensure the protection of human health and the environment. Furthermore, EU policies aim to reduce the amount of waste disposed in waste facilities and landfills by promoting waste recovery and recycling in the extractive industry (in line with circular economy principles). Thus, waste has to be intended as a "resource", and waste facilities and landfills have to be considered as a (anthropogenic) "new ore deposit" to be exploited [15], To exploit them in a sustainable manner, while protocols and operative procedures to site investigations (ref. Section 2.1) and waste volume determination (ref. Section 2.2) are needed.

2.1. Extractive Waste Facilities: From Site Investigation to EW Characterization (Physical, Geochemical, and Mineralogical Characteristics)

In order to assess the valorization potential of EW facilities, site investigations and sampling activities are needed. Those will determine the EW composition, the characteristics of the waste fractions, and the proper valorization processes that need to be applied. When planning a field survey, it is fundamental to collect specific information, such as:

- History of the mining site.
- Depth and extension of the facility bodies.
- Site investigation.
- Typology of EW materials (waste rocks, operating residues, tailings, or mix).
- Waste characterization.
- Geotechnical stability.
- Presence of possible hazardous waste placed in the landfills.

EW plants consist mainly of single-waste materials. The protocol for collecting samples representative of the EW plant under investigation is based on the appropriate number and mass of samples and the correct location within the EW plant.

During sampling activity, it is fundamental to collect EW samples accurately, both representative and in an unaltered state, to ensure a representative analysis and to obtain useful information for planning the best valorization process for the different grain-size categories and waste fractions.

Samples are generally sent to a laboratory for analysis with the aim to determine the specific characteristics of the materials.

Before starting the analysis phase, sample preparation (e.g., coning and quartering method) is useful to obtain representative sub-samples for the subsequent analysis:

1. **Physical characterization** includes EW basic characteristics, such as humidity (after drying the samples in an oven for about 24 h), bulk density and size distribution (e.g., wet particle-size analysis), and magnetic attitudes. EW characteristics are useful for the construction industry (i.e., for aggregate production), including flat index, shape index, the Los Angeles test, the micro-Deval test, the freeze–thaw test, fine-particle content, Atterberg limits, etc.
2. **Petrographic characterization** to determine the composition and properties of the mineral in the waste fractions. Petrographic observations can be performed by optical (transmitted and reflected-light) microscopy on thin-polished sections. Quantitative volume percentage determinations (i.e., modal analyses) can also be required in some cases.
3. **Mineralogical characterization** is important because the potential exploitation of RMs and CRMs from the rock is strongly linked to its mineralogy (some minerals show a better attitude to be processed for RM/CRM extraction). Thus, only certain minerals are viable for exploitation because they are economically exploitable using existing processing techniques. This analysis can be conducted through scanning

electron microscopy (SEM-EDS/WDS) and/or the X-ray powder-diffraction technique (XRPD). Other types of spectroscopic analyses (e.g., micro-Raman spectroscopy) may be required in some cases.

4. **Geochemical characterization** to evaluate RM/CRM content on representative samples (<2 mm) obtained after grinding the original sample. Whole-rock geochemical analysis can be performed with varied spectroscopic techniques, i.e., XRF for major elements, ICP-AES and ICP-MS for minor and trace elements, and electron microscopy (SEM-EDS/WDS) on polished and metalized sections/samples [16,17].

Figure 1 shows an overview of an example of a flow chart connected to the entire analytical procedure.

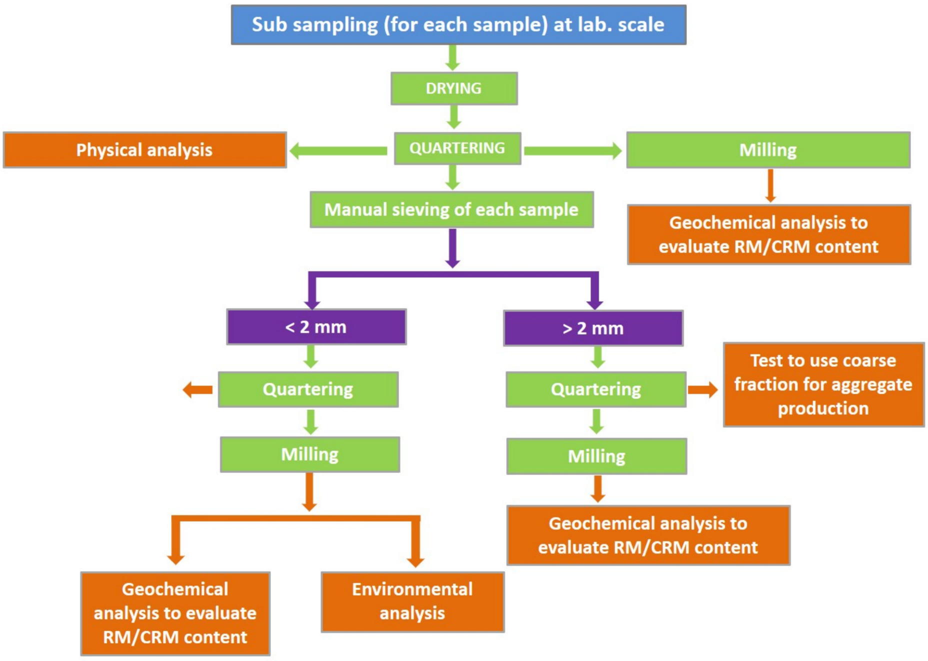

Figure 1. Protocol concerning analytical procedures [15].

2.2. *Extractive Waste Volume Evaluation (New Technologies for EW Facility Investigation)*

The volume of EW facilities can be estimated using, on the one site, the information arising from the field survey and laboratory activities (as described in Section 2.1), and, on the other site, the information accessible by "indirect" surveys gaining data from existent data bases, geophysical surveys, GIS data collection, laser scanners, etc.

The "indirect surveys" that are useful to estimate the extension, depth, and volume of EW facilities are cost-effective and save a lot of time. Apart from certain geophysical techniques, they do not require full access to the site to be studied, thus allowing the various sites to be analyzed in safe conditions for operators. They include new technologies based on the topographic and morphologic 3D characterization of the site in order to obtain a GIS-detailed reconstruction of the topographic surfaces to draw the site modeling and obtain a digital surface model (DSM). Topographic surveys on the field can be conducted by means of satellite images or aerial photogrammetric techniques (operated by a helicopter or UAV depending on site conditions). Further to this, remote-sensing techniques and a terrestrial laser scanner (TLS) can also be used.

The choice of method depends on area assets (i.e., shape, largeness): the elevation range of the investigated area influences the choice of the most suitable methods to adopt for the investigation of the extension and volume of the "anthropogenic deposit", for example. If there are available local and national spatial data sources, these data can be used as a base map for EW facility reconstruction in the cases where topographic map data are not accessible and can be collected by a survey using UAV photogrammetry or structure-from-motion (SfM) techniques [18].

After conducting the field surveys (UAV flight and ground-control point survey), post-processing activities for the data obtained are needed [10] to produce a map. After determining the total amount of EW in the EW facilities (anthropogenic deposits), it is useful to determine the real chance to exploit present RMs/CRMs thanks to the results arising from mineralogical and petrographic analyses (Section 2.1) together with the geochemical characterization of waste (Section 2.1). Indeed, only some minerals are economically exploitable by applying the existent processing techniques. Finally, to determine the residual mass amounts of a selected commodity (*X*) present in the EW facilities (as indicated "*Indicated resources*" are calculated based on waste deposits sampled in detail during the characterization study and inferred "*Inferred resources*" are calculated including also waste deposits whose characters were observed in the field, but that were not sampled and analysed. For them, resource estimates (always conservative) were made based on the metal content of the nearest sampled dump and geological considerations), Formulas (1) and (2) can be applied [10].

$$Ri\ (X) = Vi \times \rho \times G \tag{1}$$

$$Rii\ (X) = Vii \times \rho \times G \tag{2}$$

where *Ri* (*X*) = indicated resource of commodity *X*, *Rii* (*X*) = inferred resource of commodity *X*, *Vi* = volume of the EW (waste deposits sampled in detail during the characterization study), *Vii* = volume of the EW (including waste deposits whose characters were observed in the field but were not sampled and analysed), ρ = average bulk density of the EW, *G* = average grade of the commodity *X* arising from geochemical analysis (only for specific EW).

3. Issues and Potentialities Connected to EW Management

3.1. Environmental Issues

Extraction and processing activities are two fundamental phases of the mining activity (up to the metallurgic phase, which is not included in the present paper). Together with geological, hydrological, and climate conditions of the mining area, the extraction and processing phases produce different kinds of emissions that can potentially pollute the environment because of their impacts on air, water, and soil.

Extractive wastes, which represent a negative voice in the economic balance of mining activities, need to be carefully and safely managed to ensure the long-term stability of disposal facilities and prevent and minimize environmental contamination. In the following, a brief summing up the principal environmental impacts, characterized by the release of harmful substances, as well as the impact of mining activities and EW on water, soil, and air, is reported.

Impacts on water and mitigation actions:

Contaminated mine water is generated when rock-containing mineral sulfides are exposed to water and oxygen, producing acids and high concentrations of metals and sulfates in the water. This results in contaminated water that requires treatment to be reused or returned to the environment.

Mining effluents can be generated by sluicing and flushing water, acids from the extraction process, leaching, flocculation and concentration water, effluents from refining, and gas scrubbers.

Rain or groundwater that filters into the mine's deposits causes oxidation, hydrolysis, and leaching processes that result in highly polluted wastewater. Table 1 resumes the impact of mining activities and deposits on water and some mitigation actions.

Table 1. Impact on water, main causes, and mitigation actions.

Impacts on Water	Main Causes	Mitigation Actions
Changes in hydrography and hydrogeology of an area (i.e., "pit-lakes" arise during the mining productive and closure phases)	Consumption of water during the exploitation phases (from mining to processing) and interferences between the territory and mining activities. Frequent "pit-lakes" arise during the productive mining and closure phases; such lakes have to be monitored and, if needed, rehabilitated in order not to pollute land and groundwater with potential toxic elements [19,20]	Pit lakes can be reclaimed by creating new end uses, i.e.,: • For recreational activities and research [21]; • For biodiversity conservation and to guarantee water supply to the nearby area (i.e., for irrigation and/or aquaculture); • For drinking and industrial water storage; • For greenhouse carbon fixation; • For flood protection and waterway remediation; • For mine-water treatment and containment; These opportunities largely depend on water quality, slope stability, and safety concerns.
Overall management of water connected to excavation and processing phases	The excavation and processing phases involve water consumption and treatment and/or the recycling of reagents (e.g., flotation reagents, cyanide, flocculants), water management in tailing facilities, precipitation-related surface-water management, and groundwater management [22]	Recycling of water during the processing phase has significantly increased in recent decades, but 100% recycling is not possible, so some of the water removed from production cycles is present in the waste fraction (i.e., tailings, residual sludge, etc.). In order to limit water consumption and ensure more efficient recycling, various water-treatment technologies have been developed (e.g., filter-press technologies, Dorr decanters, etc.). Implementation of appropriate surface-water regulation works and the monitoring of groundwater levels, as well as the quality monitoring of surface and groundwater
Presence of reagents from mineral processing	Chemical agents and flotation agents that are used in ore dressing and metal-concentrating procedures are released into water resources. The main source of contamination is usually seepage from processing mills and tailings dams	Water treatment after release of processing chemicals and heavy metals through mine spills Vegetation and refurbishment programs at the mine sites applied for mine water contaminated by processing chemicals like polychlorinated biphenyls (PCBs) and tetrachlorobenzyltoluenes (TCBTs) [23].
Presence of (heavy) metals due to mineral concentrations in rocks	Heavy metals in mineral concentrations in rocks and an acid (low-pH) environment can be leached and transported downstream as water washes over the rock surface and EW facilities [24,25]	Acidic mine-drainage control systems (to be established in extremely acidic mine water). Reuse/recover the EW or guarantee the proper covering (with impermeable coating) in order to prevent the contamination of the water flow in EW facilities [26]. Apply a vegetation cover to prevent water contamination from the surface; this method is more economic and eco-friendly.
Formation of acid mine drainage (AMD)	Rain or groundwater that filters into the mine's deposits causes oxidation, hydrolysis, flushing, etc., which results in highly polluted wastewater. The drainage resulting from the natural oxidation of sulfide minerals that occur in ore deposits or extractive waste are exposed to weathering conditions to produce the AMD [16]. AMD can cause serious environment impacts on water (and soil) due to elevated levels of heavy metals and sulfate linked to acid generation.	Use of limestone wastes or fine residues (calcium carbonate) as a neutralizing agent to increase the pH of the water and, thus, reduce its acidity [27]. Formulate technosols for passive/reactive water treatment composed of high percentages of carbonate material and organic matter. Controlled oxidation to prevent sulfide formation (i.e., using hydrogen peroxide). Design or use of wetlands to favor the precipitation of metals (in the form of sulfides) through the action of sulfate-reducing bacteria, which work under anaerobic conditions or with low oxidation-reduction potential [28]. Prevention and covering of materials to reduce exposure to water and oxygen.

Impacts on air:

Mining activities can have a significant impact on air quality as the emission of air pollutants, dust, or the accidental release of pollutants. Table 2 summarizes the main impacts of mining activities on the air matrix.

Table 2. Impact on air, the main causes, and mitigation actions.

Impacts on Air	Main Causes	Mitigation Actions
Production of dust	Production of dust caused by exploitation, processing, transport of rocks and minerals (presence of quartz, asbestos, metals, etc. has to be monitored and faced). Dust is a generic term used to describe fine particles suspended in the atmosphere, produced during mining and processing operations (disturbance of soil and/or rocks) through mechanical action. In particular, the atmospheric dispersion of inorganic fibers and fine particles (PM2.5) can represent a risk to human health both for the workers and for the people living near the mining and processing areas.	Monitoring size, shape, and chemical composition of inorganic particles that can be released in the air.
		Preventing air dispersion of inorganic particles through irrigation.
		Limiting dust particle inhalation by using appropriate safety devices (i.e., breathing masks).
Noise and potential odors	Noise and potential odors, connected to transport, in particular, where the mining area is close to residential housing areas	The installation of acoustic barriers or screens can reduce the propagation of sound and, consequently, the noise generated by mining plants and activities.
		Planning the routes of heavy vehicles to avoid residential areas can reduce the impact of odors on sensitive areas.
CO_2 production	CO_2 production due to tracks and machineries	The reduction of CO_2 production can be achieved through the adoption of environmentally friendly vehicles and machinery (i.e., electric or hybrid vehicles), regular vehicle maintenance, and the use of vehicles with more energy-efficient engines.

Impacts on soil and mitigation actions:

Mining activities can have various impacts on the soil, both during the extraction phases and during the processing of extracted materials. Acidification, contamination, and dust generation are the main effects of mining activities on the soil. Table 3 summarizes the main impacts and possible mitigation activities.

Table 3. Impact on soil, main causes, and mitigation actions.

Impacts on Soil	Main Causes	Mitigation Actions
Dust or seepage of liquids that may cause contamination	Dispersion of dust by wind or seepage of liquids into the ground from tailings and/or waste-rock management facilities by the infiltration of rainwater or surface water: i.e., acid mine drainage [29].	To minimize the aerial dispersion of particles by the wind and the infiltration of liquids into the soil, the following measures are possible:
		• Covering the landfill body with a low-permeability soil (e.g., clay) to minimize water infiltration;
		• Applying surface stabilization to reduce the erosion until a vegetative cover is established;
		• Preventing activities of control of dust pollution by monitoring meteorological data and dust concentration [30];
		• Applying AMD treatment techniques as outlined in the section on acid effluent treatment;
Contamination of sediments	Chemical agents and flotation agents that are used in ore dressing and metal-concentrating procedures are released into water resources. The main source of contamination is usually seepage from processing mills and tailings dams	Erosion and sedimentation control can be conducted by:
		• Applying surface stabilization to reduce the erosion until a vegetative cover is established;
		• Developing a drainage-control system;
		• Removing from flow the sediment thanks to gravity settling processes;
		The control of sediment contamination can be prevented through water-treatment systems providing unpolluted water.

Table 3. *Cont.*

Impacts on Soil	Main Causes	Mitigation Actions
Effluents from controlled or uncontrolled EW facilities (tailings and waste rock)	The effluents, which are potentially toxic to humans, animals, and plants [31], can be acidic or alkaline and may contain metals and/or soluble and insoluble complex organic compounds related to mineral processing and mining operations	Acid effluents can be used as: • Limestone wastes or fine residues (calcium carbonate) as a neutralizing agent to increase the pH of the water and, thus, reduce its acidity [32,33]; • Use or design wetlands to favor the precipitation of metals (in the form of sulfides) through the action of sulfate-reducing bacteria, which work under anaerobic conditions or with a low oxidation-reduction potential [34]; • Alkaline effluents can be neutralized by adding neutralizing agents (i.e., sulfuric acid or carbonic acid) to reduce the pH.; • Alkaline ions in mining effluents can be removed through ion-exchange processes using zeolites or resins [35]; • Phytostabilization techniques to reduce the pH and the concentration of trace elements [36]; • Treatment of AMD by membranes and nanofiltration [37–39].
Vibration	Vibrations related mainly to the drill-and-blast method and the presence of tracks for the transport of block and tout-venant. Vibrations generated inside the mineral-processing plants are associated with the machinery (in particular, crushers and mills) used in the processing phase	Vibration monitoring is useful for detecting and evaluating the vibration levels generated by equipment, allowing problems to be identified and measures to be taken to reduce the impact of the vibration. Absorbent materials can help absorb and dissipate the energy of vibrations produced by equipment.

Environmental and human-health risks need to be prevented, monitored, and faced (when they occur): a specific risk analysis of the mining and quarry area is recommended. In the case of the recovery of old EW facilities, ongoing and future scenarios regarding the environmental impacts during remining and reprocessing after the closure of the new "mine" have to be forecasted in order to plan and realize the best prevention and mitigation actions.

There are several studies and applications related to environmental-impact assessment and risk-analysis methodologies [40–42] of mining activities on different ecological and environmental matrices. Some works propose the use of ecotoxicological bioindicators [43], while other procedures (i.e., ARGIA: analysis of risk for the hierarchization of mining contaminated sites) make it possible to elaborate a hierarchy of hazard centers through the compilation of various operational sheets [44]. These procedures derive from the absolute risk analysis of contaminated sites according to the principles of ISPRA's methodological criteria (*Criteri metodologici per l'applicazione dell'analisi assoluta di rischio ai siti contaminati*—APAT March 2008), which numerically defines the health risk for the users of the area and allows, if necessary, for size-remediation interventions [45]. The specific site-risk analysis is conducted using dedicated software (e.g., Risk-net 3.1.1).

The risk analysis is based on the definition of the conceptual model, which essentially consists of reconstructing the characteristics of the three main components that comprise:

Sources (of primary and secondary contamination); migration pathways (transport mechanism and exposure modes); and receptors (subjects to protect). Figure 2 shows an example of the procedure for the site-specific risk analysis based on a conceptual model connected to extractive activities, where three primary sources (mining tailings, mining waste, and mining voids) are identified, while different mechanisms of transport, such as wind (wind erosion and dispersion), surface water (erosion and solid transport), leaching, percolation and dilution in groundwater and groundwater (transport and dispersion), human exposures (inhalation, ingestion, dermal contact), and the subject hit (human receptor and water resources) are identified.

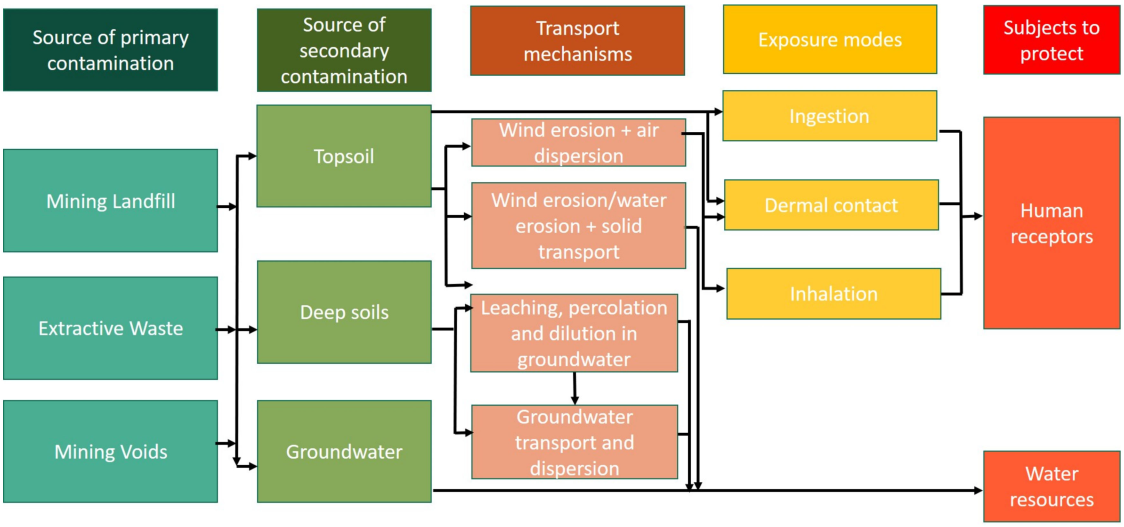

Figure 2. General outline of the procedure for the site-specific risk analysis.

The present section does not examine in depth how to approach risk analysis and mitigation actions but briefly outlines the principal impacts connected to mining and processing activities.

3.2. Raw Materials, Critical Raw Materials, and Secondary Raw Materials (RM/CRM/SRM) Present in EW Facilities, including Tailing Deposits

The present section aims to provide a general overview of potentialities connected to EW facility exploitation to contribute to the needed RM/CRM supply; indeed, extractive waste seems to have a high economic potential. The recovery of valuable by-products makes EW interesting to be exploited as they decrease their environmental footprint (Section 3.1) by reducing their volume and hazardous content.

Critical and other raw materials can be recovered from both authorized extractive waste facilities in operation/closure and from abandoned extractive waste facilities, i.e., extractive waste facilities left by the operator and not properly closed [15].

The highest metal concentrations occur in older facilities (before 1930), represented mainly by EW coming from density separation (a processing technique that was very common at that time). Unfavorable economics, inefficient processing, and mineralogical factors may also have resulted in critical metals occurring in mining wastes over time. Further to this, ore deposits that showed scarce commodity concentrations (below the cut-off grade characteristic of the time of mining) may represent valuable "new" resources to exploit thanks to the technology development and improvement of the market prices for the RMs/CRMs recognizable in the ore. There are a range of innovative technologies that can be used to liberate and separate critical metals from mining and processing waste [46]. Factors influencing the variation of metal concentration in EW are related to the composition of the original ore exploited, the type of EW, the period of deposition, the ore-processing technology applied, secondary alteration processes, the deposition of EW from different mine sites, etc. [13,47].

The approach to exploit EW facilities ("new anthropic ore deposits") is the "mining" one, which includes different steps, already presented, from waste and site characterization, to the estimation of the potential volume of EW, to the evaluation of the potential for RM/CRM/SRM supply (see Sections 2.1 and 2.2), to the individuation and quantification of the potential environmental impacts associated to such exploitation (summarized Section 3.1) [10].

The estimation of the amount of flux waste, produced during the operation of the mine, can be conducted through the knowledge of the amounts of ore produced during the exploitation activities and the specific cut-off characteristic of the mining activity [48].

Through ore gradation and the ratio of excavated-ore-to-commercial-concentrate, it is possible to estimate the weight or volume of waste generated during the life cycle of exploitation.

Underground mines, in general, have a significantly higher ore grade than an open pit mine, so the underground mine produces less waste than the open-pit mine [11].

Modern mines can guarantee the use of more modern technologies and, over the last 10 to 20 years, changes in regulations have resulted in significant developments in EW-management practices; thus, EW is now generally better managed than in the past.

Waste-management plans are often developed before a mine is operational, and rehabilitation processes for EW facilities are now always recommended by the executive plans for a new mine and are often required before a mining permit is issued [49].

Several studies exist on the development of treatment and stabilization technologies for mining waste and by-products with the aim of improving the environmental sustainability of mining operations by recycling and reusing the waste generated as raw materials for the production of other new products [50–52].

Guidelines (and best practices) on waste management and mine closures have been developed at the international level: the usual approach for EW management is to collect them at (or near) the point of production, treat EW to guarantee that they are environmentally safe, and store them in monitored EW facilities. The evaluation of cost connected to EW management (for a specific mine), their environmental performance, and the risk of failure influences the way such wastes are managed. The successful management of tailings and waste rock is based on selecting appropriate waste-storage locations and proper material characterization, including the accurate prediction of long-term chemical behavior [53,54]. Extractive waste can be used as backfill in underground or open pit workings, stored in piles on site or underwater to prevent ARD, in the construction of tracks and dams at the mine site, or recycled.

Extractive waste recovery and recycling have been investigated in several studies (scientific papers, founded projects, etc.) [55–58]. Waste rocks, operating residues, and tailings, if managed separately, and depending on the specific characteristics of the ore deposits and/or the processing and working activities, can be considered as "mono-waste" landfill and properly exploitable for RM/CRM/SRM production.

The main sectors to recover/recycle Waste Rocks and Operating Residues are presented in Table 4.

Table 4. Main sectors to recover/recycle waste rocks and operating residues.

Main Sectors to Recover/Recycle Waste Rocks and Operating Residues	Recover/Recycle Examples
Valuable RM/SRM/CRM	Not known and mined but associated to RM exploited in the past (i.e., PGE associated to Ni deposits; Ga-Ge-In-Cd associated to Zn–Pb deposits, etc. Not mined because only the minerals easier to process were exploited
Industrial Minerals	From kaolin process and granite exploitation: production of ceramic materials (ceramic bricks and tiles, roof tiles, mortars, porcelain, mullite bodies, membranes, etc.) [59,60]. Use of EW from marble and limestone to produce calcium carbonate [61]. Quartzite (ornamental stone) EW to produce quartz for glass and ceramic industry [62].
Aggregate and filler	Civil works, road paving, building industry, etc. [63–65].

Tailings (and sludge at large), which can be rich in contaminants, are often used as backfill in underground mines, stored in open pits, dried and stocked, or pumped into tailings ponds on site [66]. Several applications have been studied and tested, i.e., according to the source of the material, tailings can be used in agro-forestry (manganese tailings), in building and construction materials (clay rich tailings, manganese tailings, and bauxite red mud), to produce coating and resin (manganese tailings), in the glass industry (manganese tailings, and bauxite red mud), in the ceramic industry (bauxite red mud), and as a soil amender in waste-water treatment (bauxite red mud) [67–71].

Furthermore, fine fractions connected to dimension and ornamental stones working activities, referred to as residual sludge, can be recovered as industrial mineral for brick, mortar, and ceramic production [72,73]. Other studies investigated their employment as soil fertilizer, for the production of artificial soil, as waterproof material for landfills, etc. [74]. Tailing fraction and sludge can be exploited to produce technosols for the restoration of degraded areas. Some examples are basic technosols or technosols with a neutralizing potential to be used either as cover or over other areas to be renaturalized to grassland, technosols with a high concentration of organic matter to facilitate the establishment of reducing conditions in wetlands, and technosols for passive/reactive water treatment.

Sustainable tailing management is based on the main pillars of sustainable development that consider technological, economic, environmental, political, and social aspects. The choice of the most sustainable methods of tailings management during mining activities can be supported by decision-analysis tools (DST) [75], life-cycle assessments (LCA) [76,77] and the definition of a hierarchical system model (HSM).

EW recovery, through recycling, reuse, or reclamation, is often inefficient due to a lack of data on EW facilities and inefficient policy and governance. EU member states are required to establish and regularly update an inventory of closed EW facilities that cause or may cause a serious threat to human health or the environment [78], but it is not mandatory to collect and store information on EW facilities that potentially do not cause environmental impacts, missing the opportunity to consider these sites as a resource [79].

The inventory of EW facilities at risk on a local/national scale is generally rich in information (location, volume, characteristics, environmental impacts, company data, period of operation, etc.), but at present, there is still no general and comprehensive European database with detailed information on the distribution of EW facilities, EW characteristics, and CRM/RM/SRM content in waste.

4. Remarks and Future Perspectives

The planning of new mining operations or operations in the closure phase, risk assessment, verification, and monitoring are fundamental to a proper sustainable approach to mining waste management.

To manage and, potentially, to exploit RMs/CRMs/SRMs from old or currently active EW facilities, several information on the contents and characteristics of the specific landfill is required (see Section 2). Sampling activities to collect representative samples for EW characterization and tests on potential recoverable fractions of EW, together with volume estimation of the EW facilities, are fundamental to determine the value (in term of quantity and quality of recoverable RM/CRM/SRM) of the "anthropogenic ore deposits" represented by EW facilities.

The recovery of RMs/CRMs/SRMs from EW facilities (both closed or operating) and from fluent waste (thanks to a responsible form of mining that tends to avoid waste production from the planning to the exploitation phases) are in line with EU policy (waste recycling and natural-resource preservation). Nowadays, many of the proposed reuse and recycling concepts for EW (mainly for the waste connected to mining activities s.s.) are not economic (and, consequently, not feasible). Even when costs for exploration, as well as recovery of the material, are lower than the ones for primary ore-deposit exploitation, the ore processing concerning EW (and, in particular, tailings) might be more difficult. Consequently, the great majority of EW is still being placed into EW facilities.

Significant research efforts are required to develop cost-effective reuse and recycling options that prevent environmental impacts connected to EW management and disposal.

It is, therefore, interesting, in this sense, that the development of multi-criterion approaches considers the potential exploitation of an EW facility from various points of view: economic, but also (and especially) with regard to the environmental and social impacts [75]. This kind of analysis can help the decision-making process, favoring the alternative that minimizes the impact on the environment while being compatible from an economic and social point of view.

Examples of highly qualified effective reuse of EW are still few, but they, fortunately, exist.

Neglecting simple recovery as aggregates, the recovery of feldspar from granite waste, which has been active for several years in Northern Italy, must be highlighted. The cases of metal recovery from the EW are even more abundant. A very well-known case is the Top Star mine dump; it was constructed from 1899 to 1939, reaching a height of 50 m and containing 5.1-million metric tons of chemically processed mine waste. In the early 1960s, Top Star was converted into a drive-in movie theater, which showed movies until 2006, when it was shut down to extract residual gold in the mine waste [80].

However, it must be pointed out that many things can still be done to encourage the recovery of the EW:

- First of all, legislative initiatives to reduce the quantity of extractive waste during mining, quarrying, and processing should be adopted.
- Second, there are policy opportunities to provide financial incentives to better improve recovery processes and the reuse of EW.
- Finally, the research funding programs may be used to find suitable alternatives and substitutes for CRM. This is important because they provide an opportunity to explore other options, especially those that may be more sustainable from all social, environmental, and economic points of view.

In addition, it should be noted that, in this perspective, the role of emerging technologies such as Artificial Intelligence (AI), machine learning, and autonomous technologies, in general, in this sector can provide many economic benefits through cost reduction, efficiency, and improving productivity, as well as reducing exposure of workers to hazardous conditions, improving continuous production, and reducing environmental impacts [81].

In recent years, studies and activities related to the management of extractive waste aim at prevention, the reduction of EW production, recovery (through recycling, reuse, or reclamation), ensuring short- and long-term safe disposal of extractive waste through the whole life cycle analysis of an extractive operation, and the application of best practices promoting the Circular Economy [82].

The Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries provides up-to-date information and data on the management of extractive waste and a list of BAT to prevent or reduce any related adverse effects on the environment and human health. This document is an important reference point for the EU to select extractive waste-management activities based on site-specific characteristics and environmental risk assessments [83]. The elaboration of BAT constituted a major challenge due to the vast diversity in extractive waste activities, sectors, geography, and climatic and site-specific conditions in Europe. Further to this, to support the development of environmental-management practices for mining activities, guidelines have been developed in several countries that provide guidance on how to conduct environmental management planning by analyzing alternative methodologies, assessing impacts and risks on different environmental and human health matrices, evaluating cumulative impacts and assessing biodiversity [84,85].

Site-specific risk analysis is a methodology through which there is the chance to proactively manage the risks associated with the various phases of mining activities. Risk analysis represents a useful and supportive tool for the sustainable management of mining activities. Risk management in the mining sector has greatly developed over time over the last 20 years with a number of different tools and techniques. Risk management is an approach that assesses all risks associated with the construction, operation, and closure of the facility [86]. Indeed, a possible action to prevent (in the case of fluent waste) or reduce (in the case of old EW facilities) the environmental impacts, in the long term, is to recover RMs/CRMs/SRMs from EW.

This practice can lead to a decrease in impacts on the environment, but recovery processes (both on-site and off-site) can cause environmental impacts (on water, air, and soil, see Section 3.1) in the brief middle terms (due to the re-mining and reprocessing of waste, due to weathering actions on moved materials, etc.). Thus, new exploitation from EW facilities has to be well planned, and up-to-date technologies have to be applied to avoid the release of pollutants into the environment. A prevention program to avoid/limit the contamination of the different environmental matrixes (water, air, and soil) is needed; furthermore, a monitoring phase, to check that pollutants do not compromise the environment, has to be forecasted.

Guaranteeing the systematic recovery of RM/CRM/SRM from EW waste and exploiting non-operating (and historical) EW facilities and reducing (and monitoring) the environmental impacts can be considered as sustainable exploitation to integrate RMs/CRMs needs for EU development. The exploitation of EW and EW facilities is in line with two modern and effective approaches to waste management, such as the circular economy and landfill mining. Figure 3 schematizes the sustainable management of a "new mine": from waste prevention (due to a rational planning phase) to the recovery both of fluent EW (Figure 3, right side) and the EW present in the EW facilities, if present (Figure 3, left side).

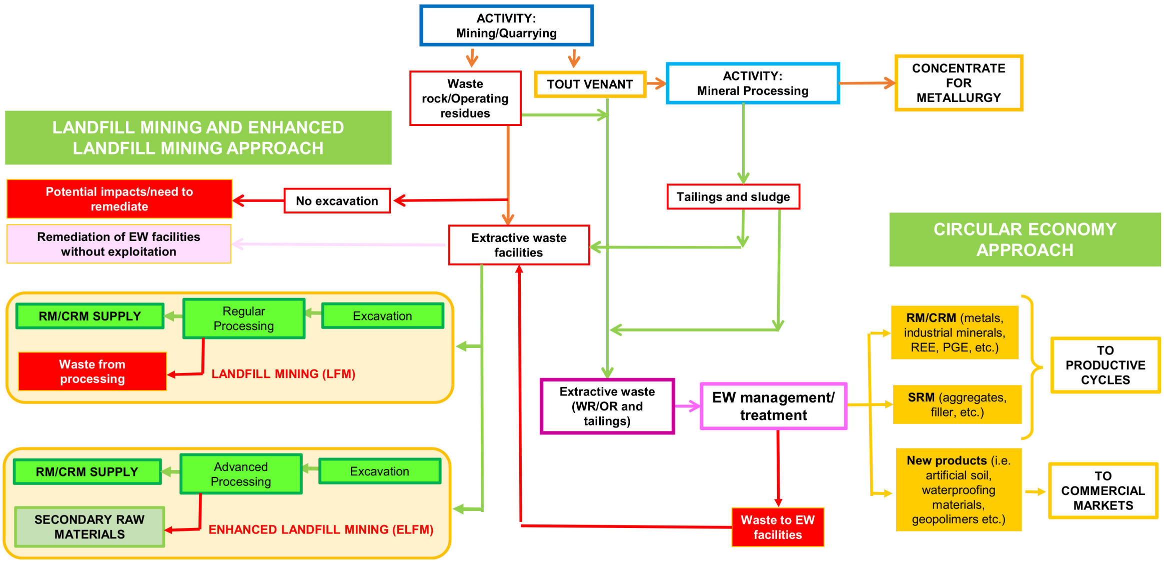

Figure 3. Future perspectives: towards LFM (landfill mining)/ELFM (enhanced landfill mining) and circular economy approaches for EW and EW facility management.

In conclusion, it has to be remarked that, to guarantee the real "sustainability" in mining sector, an interdisciplinary approach, which includes technical and environmental aspects, as well as social and economic ones, is needed.

Several actions are proposed to lead companies (even the mining ones) towards a more sustainable way of managing their business. At a global level, the Global Compact (UNGC), a United Nations initiative created to encourage companies all over the world to adopt sustainable policies linked to fundamental and universally shared principles connected to "human rights", "work", the "environment", and the "fight against corruption", has to be mentioned. This initiative was accompanied by the indication, provided by the ONU, regarding the achievement of the 17 Sustainable Development Goals (Agenda 2030) aimed at creating the necessary conditions for sustainable, inclusive, and lasting economic growth. Practical examples that companies are already trying to apply for "sustainability" are related to the inclusion and socio-economic development of young people; resilience to natural disasters; and the enhancement and conservation of cultural heritage.

At the European level, a great importance is provided to the sustainability report, which is the document that communicates the commitments made and the results obtained in the context of corporate social responsibility (CSR). Further to this, on March 2018, the European Commission published the Action Plan on Sustainable Finance Growth, which contains a series of specific measures and related deadlines, with the aim of increasing and supporting investments in sustainable projects, promoting the integration of environmental, social and governance ("ESG") criteria in risk management. In particular, the planned actions are aimed at orienting direct financial flows towards sustainable investments; managing, in a more effective way, the financial risks deriving from climate change, resource consumption, environmental degradation, and social inequalities; and improving transparency and encouraging a long-term approach in financial activities.

Ongoing research is also delving into crucial aspects such as access/licensing to old mines containing extractive waste, which have often achieved a natural equilibrium in the landscape. These kinds of activities may locally trigger new environmental issues, thereby jeopardizing mines that were previously closed due to economic reasons.

The complexity of overcoming these challenges is emphasized, especially in the European context, where many tailings have been sealed to protect populations and enhance the territory.

To address this complexity, research efforts may need to consider a multidisciplinary approach that involves also legal and regulatory frameworks.

5. Conclusions

A holistic and integrated approach to mining waste management that addresses environmental, social, and economic concerns is needed. The potential role of advanced technologies and the importance of international initiatives in promoting sustainability in the mining sector should also be highlighted.

The paper provides a comprehensive overview of various aspects related to the sustainable management of mining waste, with a focus on extractive waste (EW) and the potential recovery of valuable resources from such waste. The main key points and insights are:

1. **Importance of Planning and Risk Assessment:**
   - Proper planning and risk assessment are crucial for sustainable mining waste management, whether in the planning of new mining operations or during the closure phase.
   - Risk assessment, verification, and monitoring are essential components for a sustainable approach.
2. **Value of Extractive Waste:**
   - Extractive waste facilities represent "anthropogenic ore deposits", and understanding their contents and characteristics is vital for potential resource recovery.
   - Sampling activities and tests on recoverable fractions are necessary to determine the quantity and quality of recoverable resources.
3. **Challenges in Reuse and Recycling:**
   - While there is interest in reusing and recycling extractive waste, economic feasibility remains a challenge.
   - Legislative initiatives, financial incentives, and research funding are proposed to encourage recovery processes.
4. **Role of Emerging Technologies:**
   - Emerging technologies like Artificial Intelligence (AI), machine learning, and autonomous technologies can contribute to economic benefits, cost reduction, efficiency, and improved productivity in the mining sector.
5. **Circular Economy and Landfill Mining:**
   - The principles of the circular economy and landfill mining are considered effective approaches to waste management and resource recovery.
   - The systematic recovery of resources from extractive waste aligns with sustainable exploitation and integrates resource needs for EU development.

6. **Best Available Techniques (BAT) and Environmental Management Practices:**
    - BAT Reference Document for the Management of Waste from Extractive Industries provides guidance for managing extractive waste based on site-specific characteristics and environmental-risk assessments.
    - Environmental management practices and guidelines have been developed in various countries to address different environmental and human health aspects.
7. **Risk Management and Site-Specific Analysis:**
    - Site-specific risk analysis is essential for proactively managing risks associated with various phases of mining activities.
    - Risk-management tools and techniques have evolved over the last 20 years to assess risks related to the construction, operation, and closure of mining facilities.
8. **Interdisciplinary Approach and Sustainability:**
    - Real sustainability in the mining sector requires an interdisciplinary approach, considering technical, environmental, social, and economic aspects.
    - Actions proposed at both global and European levels emphasize the importance of sustainability reports, corporate social responsibility (CSR), and sustainable finance.

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