I4-GREEN

State of the Art Study on Mine Waste Valorisation Technologies

D6.6

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Description of the related task and the deliverable. Extract from DoA	T6.5 Development of database on mine waste and state of the art study on valorisation technologies for regional investment (M1- M24) Lead Beneficiary: JdA, Contributors: ISMC, ACPMR A study of the most important mine sites and types of mine wastes will be developed. Selected locations in Portugal and Spain (Castilla-y-Leon and Andalucia) will be highlighted. A mine waste database and report on interregional mine sites (D6.7) will be developed in M24. On the other hand, a study on the state of the art of mine waste valorisation technologies with reference to environmental and socio- economic impacts will be performed (D6.6). The data will be gathered from open sources of individual underdeveloped regions taking part in I4-GREEN (e.g., public registers of geological surveys, open reports from different sources and projects) and directly from project partners and associated stakeholders.			
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Glossary

Acronym	Meaning
EU	European Union
IP	Induced Polarization
XRF	X-Ray Fluorescence spectroscopy
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
AAS	Atomic Absorption Spectroscopy
GIS	Geographic Information System
Radar	Radio Detection And Ranging
LiDAR	Light Detection And Ranging
AI	Artificial Intelligence
IoT	Internet of Things
DTH	Down-The-Hole (drilling)
SAG	Semi-Autogenous Grinding
CRM	Critical Raw Material
REE	Rare-Earth Element
AMD	Acid Mine Drainage
MWV	Mine Waste Valorisation
VMS	Volcanogenic Massive Sulphide

Executive summary

This deliverable presents a comprehensive overview of the current state of mine waste valorisation technologies, with a particular focus on their environmental and socio-economic impacts.

In recent years mine wastes have gained more relevance, because they can represent an alternative source of critical and strategic raw materials, due to the large amounts of these elements. The report identifies and categorizes various innovative technologies used for the valorisation of mine waste. These technologies include physical, chemical, and biological methods that transform waste into valuable by-products, reducing environmental impact and promoting resource efficiency.

The technologies assessed demonstrate significant potential for mitigating the adverse environmental effects of historic abandoned mines. By converting waste into usable materials, these technologies help in reducing landfill usage and resources consumption, lowering greenhouse gas emissions, and preventing soil and water contamination when it is implemented in historic mines.

Additionally, the implementation of mine waste valorisation technologies can drive socio-economic growth by creating new job opportunities, fostering local economies, and promoting sustainable development.

1. Introduction

The mining industry plays a crucial role in supplying raw materials essential for modern technologies and infrastructure. But in order to produce these raw materials, large quantities of material have to be moved and processed, which in most cases is not utilised and is stored in waste dumps and tailings ponds. Over 1.2 billion tonnes of tailings waste have already been stored in the European Union and billions of tonnes globally with the amount growing at a rate of 5–14 billion tons per year via new production (Kinnunen & Kaksonen, 2019). The management of these materials is usually focused on restoration, to avoid potential environmental impacts; however, sometimes mining waste contains mineral resources that need to be valued.

In its efforts to combat climate change, the European Union has introduced measures like the European Green Deal and the Ecological and Digital Transition to make Europe a fairer, more prosperous, and climate-neutral continent by 2050. These initiatives necessitate a shift from fossil fuel reliance to a dependence on certain raw materials essential for green technologies. Recognizing the potential scarcity of these resources, which could hinder the development of clean and efficient technologies, the European Commission updated its Critical Raw Materials (CRMs) list in 2020, increasing the number of essential minerals from 30 to 34 in its most recent 2023 update. This list now includes key materials like copper, nickel, and arsenic. It is imperative for the European mining sector to focus on the implementation of mine waste technologies that will provide, not only economic benefits and independence from third countries for the obtention of raw materials, but also great environmental and social benefits.

In light of the current geopolitical situation, ensuring access to reliable sources of these critical raw materials has become a pressing issue for industrialized nations. The European Commission has emphasized the importance of securing a stable supply of these materials. With rising industrial demand for CRMs and the European Union's commitment to promoting a circular economy, European countries are increasingly focusing on mine wastes as a source of secondary raw materials, especially critical or strategic ones. Innovative mine waste valorisation methods are emerging as pivotal solutions to these issues, presenting opportunities not only to mitigate the possible environmental impact but also to create economic value from previously discarded mines and/or materials. By developing and implementing technologies that can recover valuable elements from mine waste, the mining industry can optimize recovery of raw materials while reducing the volume of waste requiring management and decrease the potential environmental footprint of some mining operations. This transition not only supports more sustainable resource management but also boosts economic gains by valorising discarded exploitations and by transforming waste into products that are marketable, such as rare metals, construction materials, and even new compounds for industrial use. Combining primary and secondary mineral resources mining ensures a more sustainable supply chain by balancing the exploitation of new resources with the recovery and reuse of pre-extracted/processed, ultimately reducing waste and promoting land use and circular economy. In some cases, the combination of both methods can economically justify the re-opening of a closed or abandoned mines, resulting in reviving of the mining sector and jobs. In the case of abandoned mining waste, its valorisation can simplify restoration tasks.

The global mining waste management market size reached 209.5 Billion Tons in 2023 and it has been estimated that by 2032 a total volume of 308.9 Billion Tons will be generated worldwide, exhibiting a growth rate (CAGR) of 4.41% during 2023-2032. (Research and Markets, 2023). In 2023, Europe held the second-largest share of the global mining waste management market, following Asia-Pacific. Europe's well-established framework for managing mining waste is driven by stringent environmental regulations. Among European countries, Germany is the leading generator of mining waste (Mining Waste Management, 2023).

1.1. Main Minerals and Industry in the I4-GREEN regions

The mining industry in Spain and Portugal plays a crucial role in the economy, providing essential materials for construction, manufacturing, and technology sectors. However, mining operations in these regions entail the generation of mine waste. For its part, Spain generated 41.8 million tons of mine wastes in 2020, according to the latest data offered by the National Institute of Statistics (INE). Mine wastes may present significant contents of substances included within the current list of CRMs (e.g., Co, Bi, V, Sb and Ta). In addition, they may contain other substances that, although not considered critical, are of interest as secondary raw materials and/or with strategic interest (e.g., Zn,, Ag). The type and quantity of waste depend largely on the mining method used, the processing techniques, the bed rock and the mineral being extracted. Several types of waste are generated in a mine, but three types stand out with the largest volume: waste rock, tailings and mine water (Rosario-Beltré et al., 2023).

Mining operations in Spain are governed by the Spanish Mining Law 22/1973, of 21 July, (and its regulations approved by Royal Decree 2857/1978, of 25 August) which obliges to restore, during and after the exploitation. The Mining Law also regulates the use of waste from mining activities. They are considered resources of section B: “mineral waters, thermal waters, underground structures and deposits formed as a result of operations regulated by this Law.” The Law details the priority of exploitation (Art. 31 to 33) and the Regulation details the permit application procedure (Art. 46 to 50).

In Portugal, Law 54/2015, of 22 June, regulated by the decree of law 30/2021 of 7 May, regulates the revealing and exploiting geological resources, including also the rights and obligations of environmental and landscape recovery.

Regarding the I4-GREEN regional industry, in Spain, Castilla y León has a wide range of mining operations, covering different metallic and industrial minerals, that amounted to an 11% of the total mining production in 2021 with over 3,300 employments. Regarding the production of mining waste, coal mining and roofing slate mining outstand. While coal mining has declined, there is ongoing exploration for other minerals. The coal mine waste often includes materials with a mix of minerals and coal remnants, along with associated sulphide-rich rocks, which can lead to acid mine drainage if not properly managed.

Extremadura has a varied mining potential. It lithium deposits are specially important, crucial for battery manufacturing, particularly with the growing demand for electric vehicles. Lithium mining waste can include remnant lithium content (in minerals difficult to process) as well some other elements such as Nb, Ta or Sn. In 2021, mining in Extremadura amounted to a 2% of the total production and gave place to over 1,400 jobs.

Andalucía is the richest region in mineral resources and in 2021 its contribution to the total mining production was 40% with over 8,600 employees in the mining sector. It has significant deposits of copper, zinc, and lead, especially in the Iberian Pyrite Belt, one of the world's most prominent Volcanogenic Massive Sulphide (VMS) ore clusters according to aspects like size, history or economic potential (figure 1). This district still holds 1,700 million tons (Mt) of massive sulfide with 35 Mt of zinc, 14.6 Mt of Copper, 13 Mt of led, 46,100 tons of silver and 880 tons of gold (Leistel et al, 1998; Pinedo-Vara et al, 2008). Its resulting mine waste primarily consists of pyritic materials and other sulphide minerals. This waste can be chemically reactive, leading to environmental issues such as acid mine drainage and heavy metal leaching that must be controlled and managed, but which represents a potential source of mineral raw materials if processed properly.

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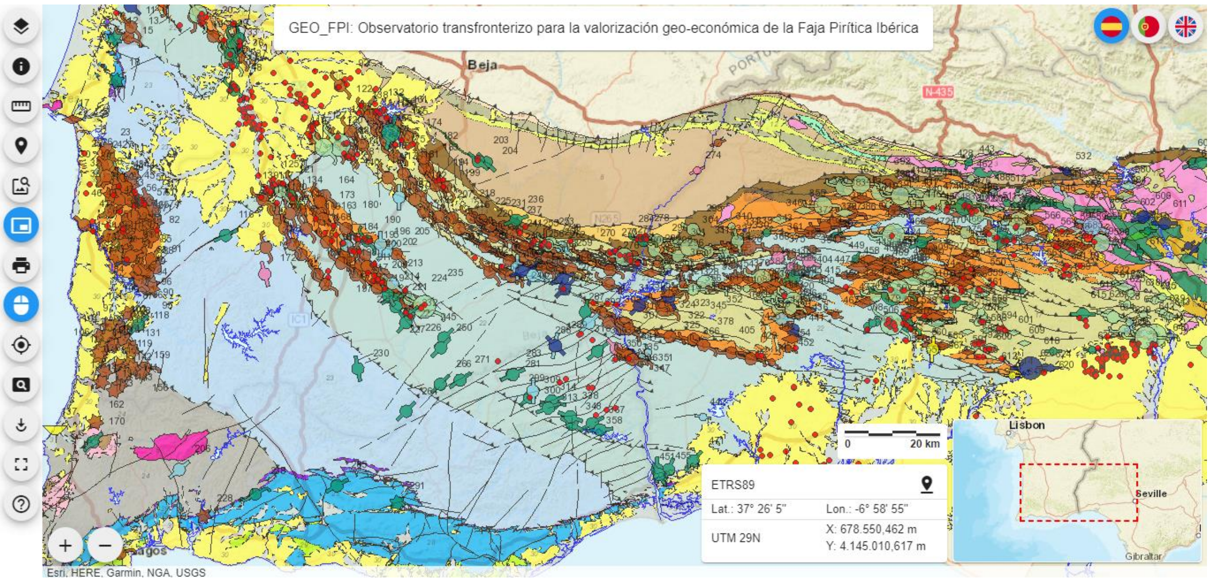

Figure 1 - Geologic and mineral deposits information for West Andalusia and Alentejo (https://info.igme.es/visor/?Configuracion=geo_fpi)

The Portuguese Alentejo region is a part of the Iberian Pyrite Belt and is notable for its large deposits of copper, zinc and lead, as well as some gold, silver and tin. The Neves-Corvo mine, one of Europe's largest copper mines, and Aljustrel mine are of great importance for the Alentejo's social and economic development. The waste is similar to that in Andalucía, with a significant presence of sulphide minerals, raising similar environmental concerns and economic opportunities.

In 2012, Portugal was one of the largest copper and tungsten producers in the EU, significantly contributing to global indium production. In 2021, Portugal's mining industry exported minerals worth €1.144 billion. The natural stone sector also ranks among the top 10 producers and exporters globally, exporting over €492 million in 2022, primarily to France, China, and Spain. The construction mineral sector has remained stable, with some declines in aggregates. Overall, the extractive industry had a production value of €1.33 billion in 2021, with €1.152 billion in exports, and employed 10,396 people. Metal ores and construction minerals dominate, representing 42% and 31% of total production, respectively.

In regions with a long and intense mining history, with large-scale open-pit mining, such as some parts of Andalucía and Alentejo, the volume of overburden and tailings is considerable. Managing these wastes effectively and sustainably is crucial for reducing environmental impacts and recovering valuable materials that can provide additional economic benefits. The mining sectors in Spain and Portugal are increasingly focused on developing and integrating waste valorisation strategies to address these challenges, aiming for a more sustainable mining practice. The I4-GREEN deliverable D6.7 (October 2024) presents additional information through its database of mine waste and interregional mine sites.

2. Types of Mining Wastes

Mining operations generate several types of waste, each with distinct characteristics depending on the type on the geology of the deposit and on the processing techniques applied. These mine wastes can pose environmental challenges, but they also present opportunities for valorisation. Below are the main types of mine wastes:

- ✓ Overburden refers to the material that lies above the mineral deposit and must be removed to access the ore. It typically consists of soil, rocks, and other materials. It is often stockpiled for use in reclamation projects or land restoration after mining.

- ✓ Waste Rock is the material that surrounds or is mixed with the ore and is removed during the mining process but does not contain economically valuable minerals, at least during the exploitation period. Waste rock can be used in construction or as backfill material. If it contains hazardous substances, it must be managed to prevent contamination.
- ✓ Tailings are the finely ground material left over after the valuable minerals have been extracted from the ore in the processing plant Tailings are typically mixed with water to form a slurry and deposited in tailings ponds. They can contain residual chemicals used in processing, as well as traces of metals and other elements. Storage is usually done through dams or tailings ponds. Newer methods like dry stacking, where tailings are dewatered and stored as solid material, are increasingly being used to reduce environmental risks.
- ✓ Slag is the byproduct of smelting ore to extract metals. It consists of non-metallic elements mixed with small amounts of metals. Slag is typically non-hazardous. It is often reused in construction, road building, or cement production. It can also be treated to extract remaining metals.
- ✓ Mine Water is water that has been used in or has come into contact with mining activities, either seeping into the mine or used during processing. Mine water can be highly acidic (acid mine drainage) or contain heavy metals. It is usually treated to remove contaminants before being discharged back into the environment or reused in the mining process.
- ✓ Sludges are semi-solid wastes produced during water treatment processes, such as the treatment of mine water or tailings water. Depending on the treatment process, sludges may contain metals, chemicals, or organic matter. Sludges are typically stabilized and disposed of in waste repositories or used in land reclamation projects.
- ✓ Mine Dust is generated during mining and processing activities can become airborne, creating environmental and health hazards. Dust is managed through dust suppression methods like spraying water or chemicals, as well as by covering stockpiles and reducing wind exposure.
- ✓ Processing Residues are the byproducts of ore processing that may still contain trace amounts of valuable minerals or other residual chemicals. They often include fine particles, chemicals, and metals used in flotation, leaching, or other processing techniques. Residues are typically disposed of in tailings ponds or treated for further resource recovery.

The environmental Concerns Related to Mine Waste can be generalised as the following:

- Leaching of Toxic Elements: Waste like tailings and waste rock can release heavy metals, sulphides, and other toxic elements into water bodies, causing contamination.
- Acid Mine Drainage (AMD): Sulphide-containing waste reacts with oxygen and water to produce sulfuric acid, which can leach heavy metals from surrounding materials, resulting in AMD.
- Tailings Dam Failures: Large-scale tailings dams, if improperly maintained or subjected to extreme weather, can fail, leading to catastrophic environmental damage.

The potential for Valorisation can be summarised as:

- Waste Rock and Overburden: Can be repurposed for construction materials such as aggregates for roads and buildings.
- Tailings: May contain residual metals that can be recovered using advanced technologies like bioleaching or chemical extraction. Tailings can also be repurposed into construction materials, such as cement or bricks.
- Slag: Often reused in road construction or as a feedstock for cement production, and in some cases, additional metal recovery can be performed.
- Mine Water: in some cases can be processed to obtain solved metals
- Mine dust: captured by spraying water, can be used depending on their characteristics

3. Modern Mine Waste Valorisation Technologies

The mining sector requires technology for its full value chain. From exploration to valorisation of waste or repurposing, technology allows to optimise results. Since some of the technologies used for mine waste valorisation are also used in previous steps of the mining process, this section presents a revision of the technologies that exist for each step prior to valorisation.

3.1. Exploration technologies

Mineral exploration involves several key technologies that enable the discovery of ores from the earth and the analysis of mining waste. Although invasive methods are still needed, modern mining exploration technologies are tending towards non-invasive advanced tools used to discover and evaluate mineral resources on Earth. These technologies include a variety of non-invasive methods and specialized equipment that help geologists and resource experts to identify and give the first steps in the characterization of mineral deposits more efficiently and accurately, instead of beginning the exploration with invasive methods.

Remote Sensing

Remote sensing and satellite imagery techniques have become fundamental tools in modern mineral exploration, offering a wide range of applications from initial exploration stages to monitoring and environmental compliance. These technologies leverage aerial and satellite platforms to collect data over large areas quickly and efficiently, identifying mineral signatures and mapping exploration areas and thus providing valuable information on the Earth's surface and subsurface characteristics without the need for direct contact.

Remote sensing technologies are evolving and improving very quickly and are very advantageous since they can cover vast areas quickly (reducing the time and cost compared to ground-based surveys) and provide valuable data in remote or difficult-to-access areas without the need for physical presence on the ground. Additionally, satellites can capture imagery of the same area over time, allowing for monitoring changes related to mining activities and environmental impacts.

- ✓ Satellite Imagery involves capturing photographs of the Earth from orbiting satellites equipped with remote sensing sensors. These sensors can detect data in multiple wavelengths of the electromagnetic spectrum, including visible light, infrared, and microwave and can identify mineral-related anomalies on the Earth's surface, such as altered rocks and soils that may indicate the presence of underlying mineral deposits. It is particularly effective in large, remote, or inaccessible areas.
- ✓ Multispectral imaging captures data at several specific wavelengths across the electromagnetic spectrum, typically less than twenty bands. Hyperspectral imaging, on the other hand, captures data in hundreds of very narrow bands, providing a continuous spectrum for each pixel. Multispectral and Hyperspectral Imaging are used to map broad mineral assemblages and specific minerals. Hyperspectral imaging is particularly powerful for detailed mapping of mineralogy and can distinguish subtle variations in soil and rock that are indicative of different types of mineral deposits.
- ✓ Infrared (Thermal) Imaging uses thermal infrared sensors to measure the heat emitted from the Earth’s surface. Variations in temperature can be indicative of different materials or changes in rock and soil properties. This technique is useful in identifying variations in rock types and the presence of faults, which may control mineralization. Also used to detect thermal anomalies associated with hydrothermal activities beneath the surface.
- ✓ Radar and LiDAR: Radar (Radio Detection and Ranging) uses radio waves to map the surface features, while LiDAR (Light Detection and Ranging) uses light pulses. Both methods measure the time it takes for the signal to return after hitting the surface, providing precise topographical data. Radar is particularly useful in cloudy or forested areas as it can penetrate cloud cover and vegetation. LiDAR provides high-resolution elevation data and is excellent for mapping geological structures and understanding landscape morphology, which is crucial for mapping potential pathways of mineral deposits.
- ✓ Photogeology involves the interpretation of geological features from aerial photographs and satellite images, focusing on identifying rock types, structures, and geological formations

visible on the surface. It is a technique used to map large, exposed areas for structural features such as faults, folds, and lineaments, which may control mineralization.

Integrating remote sensing data with geophysical and geochemical data provides a comprehensive understanding of an area's geological setting. This multi-disciplinary approach is crucial for successful mineral exploration and ongoing environmental monitoring.

Remote sensing and satellite imagery have revolutionized mine exploration by providing extensive, accurate, and up-to-date data, facilitating more informed decision-making and efficient resource management while minimizing environmental disruption.

Drone Technology

Drone technology has rapidly become a vital tool in modern mineral exploration and monitoring. Drones offer a flexible and cost-effective means of collecting high-resolution data from the air, providing detailed insights into geological features, vegetation cover, and other critical environmental factors. Drones are used in some of the technologies mentioned earlier:

- ✓ Aerial Photogrammetry
- ✓ Thermal Imaging
- ✓ Multispectral and Hyperspectral Imaging
- ✓ Magnetic Surveys
- ✓ LiDAR Scanning

Drones can be quickly deployed, fly at lower altitudes than manned aircraft and access hazardous or inaccessible areas, allowing them to capture extremely high-resolution imagery and data and often provide it in real time enabling fast decision-making. Furthermore, they offer a more affordable option compared to full-scale aerial surveys conducted by manned aircraft, especially for small to medium-sized areas.

On the other hand, drone operations are subject to regulatory controls, which can vary significantly between jurisdictions and may limit their use in certain areas or altitudes and their limited battery life of drones can restrict their operational range and the size of the area they can cover in a single flight.

Geochemical Techniques

Geochemical techniques provide vital clues that guide more intensive exploration efforts and reduce the overall environmental footprint of mining activities by focusing resources on the most promising areas. They involve the systematic collection and chemical analysis of rock, soil, sediment, water, or vegetation samples with techniques such as X-ray fluorescence spectroscopy (XRF), inductively coupled plasma mass spectrometry (ICP-MS), and atomic absorption spectroscopy (AAS), which provide information on the presence and concentration of mineral deposits at various depths, depending on the medium sampled (e.g., deep-rooted plants for biogeochemistry) and are commonly used in the early stages of exploration to narrow down target areas for more detailed investigation.

- ✓ Stream Sediment Geochemistry involves collecting sediment from streams and rivers. The rationale is that erosion and runoff from mineralized areas transport metal ions and fine-grained minerals downstream, which deposit in sediments. This technique is effective for regional-scale exploration and in identifying mineralization in upstream areas. Particularly useful in terrains where bedrock is covered by vegetation or soil.
- ✓ Soil Geochemistry is based on the analysis of soil samples taken at various depths and locations to detect geochemical anomalies. Elements found in soils can be traced back to their parent materials, which may include ore bodies. Soil sampling is widely used in the exploration of gold, copper, nickel, and other base metals. The choice of sampling depth and spacing depends on the targeted mineral and the expected depth of mineralization.
- ✓ Lithogeochemistry involves collecting samples of rock exposures, which are then crushed and analysed for their elemental composition. This method provides direct information about the

mineral content of the exposed rock and is essential for mapping and defining ore grades and boundaries in exposed mineralized zones.

- ✓ Water Geochemistry analyses the chemical composition of water from springs, wells, or boreholes, which can reveal the presence of metals and other elements that leach out from mineral deposits. It is very useful in areas with a high groundwater flow, where soluble metals or indicator elements from ore bodies might migrate into local water systems.
- ✓ In the biogeochemistry technique, plants absorb certain elements from the soil and water. By analysing the chemical composition of plant tissues, particularly leaves, researchers can identify anomalies that may indicate the presence of mineral deposits below the surface. This is especially useful in regions where the bedrock is deeply weathered or covered by thick vegetation, making direct sampling difficult.

Modern exploration often integrates geochemical data with geological, geophysical, and remote sensing data to create a comprehensive model of the subsurface. Advanced statistical methods and geographic information systems (GIS) are used to analyse and visualize the data, helping to pinpoint areas of interest more accurately.

Geophysical Techniques

Geophysical techniques are critical tools in mineral exploration, allowing geologists to create maps of subsurface structures and identify potential ore deposits or characterise mining waste deposits with minimal environmental impact. These methods are usually non-invasive (no surface disruption) and can cover large areas quickly, providing valuable data that can guide more detailed exploration efforts at a lower cost than drilling.

These geophysical techniques are instrumental in modern mineral exploration, offering a blend of efficiency, cost-effectiveness, and reduced environmental impact, making them indispensable in the search for mineral resources.

- ✓ Magnetic Surveys measure variations in the Earth's magnetic field caused by magnetic minerals like magnetite. The presence of these minerals can indicate potential ore deposits. Widely used in the exploration for iron ore, nickel, and cobalt, these surveys can be conducted from the air (aeromagnetic), from the ground, or from sea.
- ✓ Gravity Surveys measure variations in the Earth's gravitational field which can be affected by differences in the density of underground rocks. Higher density can indicate the presence of certain ore bodies. They are useful for detecting denser ores like lead, gold, and other metallic minerals. These surveys can also help map the subsurface geology and structure, providing clues about potential deposit locations.
- ✓ Electromagnetic Methods measure the ground's ability to conduct electricity, which changes depending on the type of rocks and minerals present. They involve transmitting an electromagnetic field into the ground and measuring the response. These techniques are particularly effective in exploring for base and precious metals like copper, gold, and silver. They can also be used to detect sulphide and graphite ores.
- ✓ Seismic Reflection and Refraction methods involve sending shock waves into the ground using controlled energy sources such as explosives or mechanical impacts. The waves that bounce back from underground layers are recorded and analysed to infer geological structures. Although more commonly associated with oil and gas exploration, seismic methods are also used in mining to delineate deep geological structures that could host mineral deposits.
- ✓ Electric Surveys: Resistivity and Induced Polarization. Resistivity involves passing an electrical current through the ground and measuring resistance, which varies according to the materials present. Induced Polarization (IP) measures the capacitive action of subsurface materials, which helps detect materials that can hold an electrical charge temporarily. These techniques are effective for identifying sulphide minerals, clay, and other conductive materials. IP is especially useful in the exploration of gold, copper, and other metallic minerals.

- ✓ Radioactive Methods detect natural or induced radioactivity in the ground. Gamma-ray spectrometry, for example, measures natural gamma radiation from the decay of isotopes in rocks. It is key in exploring for uranium, thorium, and potassium-rich minerals. Also used for general geological mapping.

Modern exploration often integrates multiple geophysical techniques to improve accuracy and reliability. For instance, combining magnetic and electromagnetic surveys can provide a more comprehensive view of the subsurface, helping to reduce exploration risks and focus drilling activities more effectively.

Trenching

Trenching refers to the process of digging shallow, linear excavations or trenches in the earth to expose and sample sub-surface materials. It is primarily used in exploration to determine the mineral content and geological characteristics of an area. Trenches are often used to examine the near-surface bedrock and to collect samples, allowing for a detailed understanding of the geological structure of a site, as it exposes larger surface areas compared to drill cores. It is especially useful in initial exploration stages and is commonly employed in mining for gold, base metals, and other minerals.

Drilling

Drilling refers to the process of digging shallow, linear excavations or trenches in the earth to expose and sample sub-surface materials. It is primarily used in exploration to determine the mineral content and geological characteristics of an area. Trenches are often used to examine the near-surface bedrock and to collect samples, allowing for a detailed understanding of the geological structure of a site, as it exposes larger surface areas compared to drill cores. It is especially useful in initial exploration stages and is commonly employed in mining for gold, base metals, and other minerals.

Automated and AI-driven Technologies

Automated and AI-driven technologies are revolutionizing mineral exploration by increasing the efficiency, accuracy, and depth of analytical capabilities. These technologies are particularly useful in processing vast amounts of data collected through various exploration activities and in making predictive analyses that guide exploratory decisions. Automation and artificial intelligence (AI) are being applied in the field of mineral exploration through:

- ✓ Machine Learning Models in Predictive Analysis: Machine learning algorithms can analyse geological, geochemical, and geophysical data to identify patterns and correlations that may not be evident through traditional analysis methods. AI models can predict the likelihood of mineral occurrences by learning from known data about mineral deposits. These models can integrate various data types, including drilling results, sampling data, and historical exploration data, to make predictions about mineralization zones.
- ✓ Automated Drilling and Sampling: Advanced robotics and automation technology are used to perform drilling and sampling operations with minimal human intervention. These systems are designed to operate under harsh environmental conditions and can be remotely controlled. Automated drilling rigs can execute drilling operations more consistently and accurately than manual methods. Automation in drilling not only speeds up the exploration process but also enhances safety by reducing human exposure to hazardous conditions.
- ✓ Data Integration and 3D Modelling: AI-driven tools can integrate disparate data sources into a cohesive model that provides a three-dimensional visualization of subsurface geology. This capability allows geologists to better understand the geological context of an area, improving the accuracy of targeting ore bodies. 3D models are dynamically updated with new data, providing a real-time view of the exploration progress and insights.
- ✓ Remote Sensing Data Analysis: AI algorithms can process large datasets obtained from remote sensing technologies, such as satellite imagery and aerial surveys, more efficiently than traditional methods. It can detect anomalies in vegetation, soil colour, and other surface

features that may indicate underlying mineral deposits. It can also process thermal and hyperspectral imaging data to identify specific mineral signatures.

- ✓ Autonomous Vehicles and Drones equipped with various sensors are used for mapping, surveying, and monitoring mineral exploration sites. These vehicles can cover large areas quickly and gather data with high precision. They are particularly useful in inaccessible or dangerous terrains, reducing the risk to human surveyors.
- ✓ Real-time Monitoring and IoT: The Internet of Things (IoT) involves a network of sensors and devices connected over the internet, which collect and exchange data in real-time. In mineral exploration, IoT devices can monitor environmental conditions, equipment status, and other critical factors. This data is continuously analysed by AI systems to optimize exploration strategies and ensure compliance with environmental regulations.
- ✓ Natural Language Processing (NLP) enables computers to understand and interpret human language as it is spoken or written. It can be used to analyse and extract information from scientific reports, previous exploration documents, and other textual data sources, aggregating historical knowledge that can guide new exploration projects.

These technologies can process and analyse data much faster than human capabilities, speeding up the exploration phase. By optimizing exploration activities and reducing the need for extensive manual labour, costs are significantly lowered. Automation reduces the need for human presence in potentially dangerous exploration sites, thereby enhancing safety.

However, implementing AI and automation technology requires significant upfront investment in software, equipment, and training. Additionally, AI models are only as good as the data they train on. Poor quality or biased data can lead to inaccurate predictions.

As these technologies continue to evolve, their integration into mineral exploration is likely to deepen, offering even more sophisticated tools for discovering and managing mineral resources efficiently and sustainably.

3.2. Exploitation Technologies

Mineral exploitation, commonly referred to as mineral extraction, involves several key technologies that enable the efficient extraction of ores from the earth or recovery valuable minerals from mining waste. The major technologies employed in this process include drilling, blasting, ore extraction, and material handling. Each plays a crucial role in ensuring that mining operations are safe, efficient, and environmentally conscious, but material handling is the main technology used for exploitation of mine waste

- ✓ Material handling in mining operations involves moving, processing, and storing the extracted ore and waste materials:
  - Conveyors Belt: Conveyors transport material efficiently over large distances. They are crucial in both surface and underground mines.
  - Loaders and Trucks: High-capacity loaders and haul trucks are used to move large amounts of ore and waste rock to processing sites or waste disposal areas.
  - Automated Haulage Systems: These systems use autonomous vehicles to increase efficiency and reduce labour costs. They are increasingly common in large-scale mining operations.
  - Stockpile Management: Advanced stockpile management techniques use real-time data to optimize the blending, reclaiming, and processing of different ores to maintain consistent feed quality to the processing plant.
- ✓ In the context of mining waste management, liquid waste transport involves the collection, conveyance, and treatment of liquid residues generated during mining activities, such as water used in ore processing, tailings ponds, and other wastewater streams. The goal of transporting these liquid wastes to a valorisation plant is to recover valuable materials or reduce

environmental impacts through treatment, recycling, or reuse of the water or contained minerals.

Modern mining operations often integrate these technologies with advanced monitoring systems that provide real-time data on equipment performance, environmental conditions, and worker safety. These systems help to optimize operations and reduce environmental impacts through better waste management, reduced greenhouse gas emissions, and minimized landscape disturbance.

3.3. Processing technologies

Processing technologies in mining and mine waste recovery play a critical role in the modern mining industry, focusing on both maximizing resource extraction and minimizing environmental impacts. Technological innovations not only help reduce waste but also align with the principles of the circular economy, turning what was once considered waste into valuable resources. As the demand for minerals increases, particularly for green technologies, the development of efficient and sustainable mining waste recovery technologies has become crucial for both economic and environmental sustainability.

Physical Methods

Physical methods for mine waste valorisation involve techniques that primarily use physical forces such as gravity, magnetic properties, or particle size to separate valuable materials from the bulk waste. These methods are crucial in the recycling and recovery of valuable elements from mining waste, helping to reduce the environmental impact of mining activities and enhancing resource efficiency.

- ✓ Screening involves the separation of materials based on particle size using various types of screens or sieves. Fine particles pass through the screen while larger particles are retained. It is often used to separate valuable minerals from coarse waste rock or to prepare the waste for further processing steps. It is particularly useful in segregating particles before applying more complex and cost-intensive treatments. Hydrocyclones are used in conjunction with or as an alternative to screens. These use a centrifugal force to classify particles by size or density.
- ✓ Gravity Separation exploits differences in the specific gravity of materials to separate valuable minerals from less dense waste components. Techniques include jigging (An older form of gravity separator where particles are sorted by repeated expansion and contraction of a bed which causes heavier particles to sink to the bottom), shaking tables and spiral concentrators (modern gravity separation equipment that uses water flow and gravity to separate lighter materials from heavier ones.), and dense media separation. It is effective for recovering heavy minerals from tailings, such as gold, tungsten, and chromite. It is energy-efficient and does not require the use of chemicals, making it environmentally friendly.

- ✓ Magnetic Separation utilizes the magnetic properties of minerals. Materials are passed through magnetic fields, which attract ferromagnetic and paramagnetic materials from non-magnetic ores, while leaving diamagnetic materials unaffected. It is widely used to recover ferrous metals like iron and nickel from waste. Also effective in separating some non-ferrous metals that exhibit paramagnetic properties under certain conditions.
- ✓ Electrostatic Separation utilizes differences in electrical conductivity to separate conductive minerals materials are charged and then subjected to an electric field, causing them to be attracted to electrodes based on their conductivity and charge. It is most useful for the separation of conductive minerals like copper, zircon, and certain types of coal from insulating materials (e.g., quartz and silicates).
- ✓ Comminution is the process of reducing the size of ore to facilitate further processing. Jaw crushers, gyratory crushers, and cone crushers break rock by compressing it between hard surfaces. Ball mills, rod mills, and SAG (Semi-Autogenous Grinding) mills further reduce ore

to a fine powder or slurry. This step is crucial to increase the surface area of the ore, enhancing chemical reactions in subsequent processing stages.

- ✓ Flotation is a widely used technique for processing complex ores, including those containing multiple metals. Here, ore slurry mixed with water and reagents is aerated in flotation cells. The reagents cause desired minerals to become hydrophobic (water-repellent) and attach to air bubbles which float them to the surface, forming a froth that is skimmed off.
- ✓ The final step in mineral processing is often dewatering, which reduces moisture in the mineral concentrate. Thickeners are used to concentrate slurries by settling out solids and decanting water. Filter presses and vacuum filters remove more water, producing a dry cake of minerals which is easier to handle and transport.
- ✓ Sensor-Based Sorting involves advanced sensors to detect specific characteristics of particles, such as colour, X-ray transmission, or near-infrared properties. Based on these characteristics, a mechanical system separates the valuable particles from waste. It is increasingly used for pre-concentration of ores to reduce energy and water usage in downstream processing. Effective in sorting base metals, precious metals, and gemstones.

Physical methods typically use less water and energy than chemical processing techniques and do not generate chemical waste. They can significantly reduce the volume of waste to be stored or treated, lower handling costs, and recover valuable materials that can be sold. However, often, physical methods are less effective with very fine particles or when the minerals are closely associated with waste materials.

Some advanced physical techniques like sensor-based sorting require significant capital investment and are technology-intensive.

The choice of physical methods depends on the characteristics of the mine waste and the specific minerals to be recovered. As technology advances, these methods are becoming more sophisticated, offering higher recovery rates and better environmental performance. Certain mine wastes, especially those from the processing of minerals like phosphates, bauxite, or iron ore, contain low concentrations of rare earth elements (REEs). These can be extracted and purified for use in various high-tech applications. REEs are critical in the manufacture of electronics, magnets, and batteries.

Chemical Methods

Chemical methods are essential for recovering valuable resources that might not be economically feasible to extract using physical methods alone, especially when dealing with fine particles, complex mineral matrices, or low-grade ores.

- ✓ Hydrometallurgy involves the use of aqueous solutions to leach metals from ores, concentrates, or waste materials. The process typically includes three main steps: leaching, solution concentration, and metal recovery. Common leaching agents include acids (sulfuric, hydrochloric), alkalis (sodium hydroxide), and other complexants. It is widely used for extracting copper, gold, silver, and uranium. For example, gold can be extracted using cyanide leaching, while copper is often recovered using sulfuric acid leaching.
- ✓ Bioleaching is a subset of hydrometallurgy that is also considered a biological method, since it uses microorganisms to biologically oxidize or reduce ores, thereby facilitating metal solubilization without the need for high temperatures or pressures. Microbes such as bacteria and archaea naturally process sulphide minerals and liberate metals in a form that can be recovered. It is effective for low-grade ores and tailings, particularly for copper, gold, and uranium extraction. It is environmentally favourable compared to traditional chemical methods due to lower energy consumption and less hazardous chemical use.
- ✓ The Solvent Extraction process involves the transfer of a solute from one liquid phase into another liquid phase in which it is more soluble. After leaching metals into a solution, solvent extraction is used to separate specific metals from a complex mixture by using an organic

solvent. It is primarily used in the purification and concentration of metals such as copper, nickel, and rare earth elements from leach solutions.

- ✓ Electrowinning is a technique that involves passing an electric current through a metal-laden solution, causing metals to deposit onto a cathode. This method is typically used in conjunction with solvent extraction. It is most used for copper, zinc, and precious metals recovery. It is highly efficient for producing high-purity metal products directly from leached solutions.
- ✓ Although Flotation has physical components (as it involves the creation of bubbles that physically bind to hydrophobic materials and bring them to the surface in a froth that can be skimmed off), flotation is primarily a chemical process that separates hydrophobic materials from hydrophilic ones. Reagents are added to a slurry of ore or tailings to create conditions where the desired minerals attach to air bubbles and rise to the surface in a frothy layer that can be skimmed off. It is particularly effective for fine particles and is extensively used of the recovery of sulphide ores such as copper, lead, and zinc from pulverized ore or tailings. It is also used to recover small-sized precious metals like gold and silver from complex ores.
- ✓ Chemical Precipitation involves the transformation of dissolved metal ions into solid particles through chemical reactions. Precipitating agents induce the formation of insoluble compounds which can then be filtered from the solution. It is used to remove and recover heavy metals from waste streams, including cadmium, chromium, and nickel.

Chemical Methods can handle low-grade ores and complex mineralogies where physical separation is ineffective. Furthermore, they can be very selective for certain metals, allowing for the recovery of specific target materials from diverse waste streams.

However, from an environmental impact point of view, the use of chemicals, especially in processes like cyanide leaching and acid mine drainage, can pose significant environmental risks if not properly managed. Additionally, chemical treatments can be expensive due to the cost of reagents, energy, and the need for robust waste management systems to handle the byproducts and residues.

Overall, chemical methods for mine waste valorisation offer powerful tools for extracting value from waste, but they require careful management to balance efficiency, cost, and environmental stewardship.

Biological Methods

Biological methods utilize living organisms or their metabolic processes to extract valuable metals from mine waste. These techniques are often considered more environmentally friendly compared to traditional physical and chemical methods, as they typically operate at ambient temperatures, use less energy, and generate fewer pollutants.

- ✓ Although Bioleaching is generally considered a chemical method (see it described also under 'chemical methods'), it involves using microorganisms to facilitate the breakdown of minerals in the waste, thereby releasing the metals into a solution from which they can be recovered. The microorganisms—typically bacteria such as *Acidithiobacillus ferrooxidans* and *Leptospirillum ferrooxidans*—oxidize sulphide minerals, resulting in the solubilization of metals. This technique is commonly used for the recovery of copper, zinc, gold, and uranium from low-grade ores and tailings. Bioleaching is particularly effective with sulphide-rich ores.
- ✓ Phytomining (also known as Agromining) is the use of bacteria or plants to extract metals like gold, copper from waste. It involves growing plants that can absorb, concentrate, and precipitate metals from the soil into their biomass. Once the plants reach a sufficient level of metal concentration, they are harvested and incinerated, and the ash is then processed to extract the metals. It is effective for recovering nickel, cobalt, thallium, and rare earth elements. Certain plants, known as hyperaccumulators, are used because of their ability to concentrate high levels of metals.

- ✓ The Phytostabilization technique uses plants to immobilize contaminants in the soil and mine waste, preventing their spread via air or water. While it does not involve actual extraction of metals for economic use, phytostabilization helps in mitigating environmental damage, making it a valuable component of integrated mine waste management strategies. It is generally used for stabilizing lead, arsenic, and cadmium in contaminated soils and mine sites. It reduces the bioavailability of the metals, thereby preventing them from entering the food chain.
- ✓ Constructed Wetlands are engineered systems that use natural processes involving wetland vegetation, soils, and their associated microbial assemblages to improve water quality. These systems can be designed to treat contaminated mine water, precipitating out metals and other pollutants. They are effective in removing a range of pollutants, including heavy metals like zinc, copper, and lead, as well as nitrates and phosphates.
- ✓ Although still largely experimental, Microbial Fuel Cells use bacteria to oxidize organic and inorganic matter and generate electricity. When applied to mine waste, these cells can potentially extract metals while simultaneously producing energy. Research is ongoing, but potential applications include recovery of copper and cleaning of waters contaminated by mine discharge.

These methods typically have a lower carbon footprint, use less energy, and produce less pollution compared to chemical methods and have higher social acceptance: they are often viewed more favourably by local communities and regulators due to their greener profile.

However, operating and capital costs can be lower, especially when local plants or naturally occurring bacteria are utilized. Furthermore, biological processes are often slower than chemical methods, which implies a low rate of recovery and thus a drawback for large-scale commercial applications. Additionally, biological systems can be sensitive to pH, temperature, and the presence of toxic substances, which may limit their effectiveness under certain conditions.

Biological methods for mine waste valorisation offer a promising avenue towards more sustainable mining practices, providing both environmental benefits and potential economic opportunities. As research continues to advance in this field, these technologies are expected to become more efficient and widely applicable across different types of mine waste.

Modern mineral processing plants increasingly integrate advanced technologies such as:

- ✓ Process Control Systems: Use sensors and computer technology to monitor and adjust processing operations dynamically.
- ✓ Machine Learning and AI: Analyse data from the processing stages to optimize parameters for improved recovery rates and efficiency.

Re-purposing Efforts

At a first step, the valorisation process is focused on the main interesting minerals, (CRMs or strategic minerals) that can make valuable a mining waste. However, these are usually a small part within the whole volume of waste. After the treatment, the volume doesn't vary significantly, so, from the point of view of circular economy, the real interest is finding a reuse for the whole waste. Re-purposing mine waste for valorisation involves transforming waste materials from mining operations into useful products or applications, thereby reducing environmental impacts and potentially generating economic benefits. These efforts are critical as they contribute to a more sustainable approach to handling and significantly reducing the massive volumes of waste generated by the mining industry.

- ✓ Construction Materials:
  - Concrete and Cement: Mine tailings can be used as a partial replacement for cement in concrete production. The fine particles of tailings are suitable for the concrete mix, enhancing its strength and durability while reducing the carbon footprint associated with cement manufacturing.

  - Bricks and Tiles: Tailings and other waste rocks can be processed into bricks and tiles for construction. The thermal properties of certain mine waste can improve insulation, while their aesthetic qualities can enhance architectural design.
  - Road Base and Aggregates: Crushed waste rock can serve as a substitute for natural aggregates in road construction and other civil engineering projects. This not only helps in utilizing large quantities of waste but also reduces the extraction of natural resources.

  These materials are basically obtained by means of physical methods, usually comminution and screening

- ✓ 'Silicate and mineral-rich' mine waste can be used for Ceramics production: tiles, tableware, and other ceramic products.
- ✓ Land Reclamation and Remediation: Mine waste can be used to fill abandoned mine pits or to landscape areas degraded by mining activities. This aids in stabilizing the terrain and reducing erosion. It is used for the creation of green spaces, agricultural land, or recreational areas on rehabilitated mine sites. This can help in restoring ecological functions and providing community benefits.
- ✓ Geo-polymers are inorganic polymers produced from aluminosilicate materials, which can include certain types of mine tailings. Used as a more sustainable alternative to Portland cement in construction, geo-polymers offer superior mechanical properties and resistance to chemicals, heat, and fire.
- ✓ Finally, in a very minor scale, mine waste materials, especially those with unique colours and textures, can be used in the creation of Art and/or Decorative Items: sculptures, jewellery, and other craft products can be produced from transformed mine waste, adding cultural and artistic value.

The cost-effectiveness of re-purposing efforts depends on local market conditions, regulatory incentives, and the scale of operations. Moreover, some uses require pre-processing and treatment of the waste to meet safety and performance standards, which can involve significant technological and logistical challenges. Compliance with environmental standards is crucial, especially when dealing with potentially hazardous materials.

Re-purposing mine waste for valorisation not only helps in waste management but also contributes to resource conservation, thus supporting the transition towards a more circular economy. As technology advances and regulatory frameworks evolve, the scope and impact of these efforts are expected to grow, further integrating waste valorisation into sustainable development strategies.

4. Mine Waste Recovery Projects in Spain

Currently, there are several outstanding research projects on the re-mining of mine wastes in Europe, in which Spain and Portugal are participating:

The NEMO project "Near-zero-waste recycling of low-grade sulphidic mining waste for critical-metal, mineral and construction raw-material production in a circular economy'" was a EU H2020 Innovation Action project that finalised in 2022. With several pilots, and case studies in Finland and Ireland, NEMO developed, demonstrated and exploited new ways to valorise sulphidic mining waste.

SULTAN is a Horizon 2020 project that provided the first-ever training programme dedicated to the reprocessing of tailings. The project pooled interdisciplinary and intersectoral expertise covering all the links in the tailings-reprocessing value chain, to develop cutting-edge methodologies to assess the resource potential of Europe's main tailings families and explores eco-friendly mining chemicals to be used in advanced metal-extraction/recovery set-ups. SULTAN not only amied to recover the metals but also valorise the clean(ed) tailing residues in circular-economy applications, incl. inorganic polymers, green cements and ceramics, and develops a novel environmental assessment methodology. The 15 SULTAN ESRs also benefited from a unique soft-skills training programme to kick-start their careers as highly employable professionals in the EU's tailings reprocessing/remediation sector, as well as for geological surveys, teaching and scientific organisations, and public bodies.

The EU H2020 CROCoDILE project showcased an innovative metallurgical system, based on advanced pyro-, hydro-, bio-, iono- and electrometallurgy technologies, for the recovery of cobalt and the production of cobalt metal and upstream products. A wide variety of secondary and primary European resources as feedstocks. CROCODILE pro-actively engaged with local and international civil society groups, to obtain and maintain the Social License to Operate for cobalt recovery and production.

The Horizon 2020 TARANTULA's overarching objective is to develop a toolkit of novel, efficient and flexible metallurgical technologies with high selectivity and recovery rates with respect to W, Nb and Ta. As such, the project will promote (i) sustainable annual supply of secondary W at an amount equivalent to 50% of current EU W primary production, (ii) exploitation of Ta content equivalent to at least 120% of EU annual demand (iii) exploitation of Nb content equivalent to at least 5% of EU annual demand.

RAWMINA is a Horizon Europe project that will develop an industrially scalable Mine Waste valorisation pilot in the Iberian Penninsula, which involves continuous operation, excellent recovery and selectivity for Cobalt, Antimony, Germanium and Tungsten, additional recovery of Gold, Silver and Iron-based by-products, reutilising 90% of water. Treating up to 100-150 kg mine waste per day, and efficient, circular and robust process control. To achieve this, the project activities include mine waste conditioning and characterisation, optimisation and upscaling of innovative process technologies, continuous bioleaching, iron removal with magnetic separation, selective recovery using danofibrous composite materials, thermo-desorption process, electrowinning and electrocoagulation and process simulation, system engineering & demonstration

REVIVING is a ERAMIN2 project that aims to validate an innovative, clean, and cost-effective bioprocess for recovering metals from mine waste, contributing to the EU's shift toward a circular economy. By manipulating the microbiome of tailings from mines in Portugal and Romania, the project focus on leaching critical and non-critical metals such as Cu, Mn, Zn, Mo, W, and Mg. Small-scale assays are testing this process, which promises to achieve zero mine waste and restore lands for agricultural and social use, positioning the EU as a leader in raw materials processing technologies.

As a particular case in Spain, the project for the recovery of tantalum and niobium from the mine wastes of the old Penouta mine, located in the central area of the Iberian Peninsula, is currently underway.

4.1. The I4-GREEN Project Technologies for MWV

Iron Holm Oak Pilot

The IHO Pilot is an industrial-mining project focused on the recovery of endogenous resources, (including EU strategic raw materials such as rare earth elements (REE), from tailings of the iron ore processing) incorporating modern technologies, under high criteria of environmental, social and economic sustainability. Through the project, this sustainable commitment is complemented with water recycling, green energy, sustainable operation, automation, sustainable mobility, circular recovery, digitization and community integration. Through the I4-GREEN Open Call IHO is also focusing on:

- Life Cycle Assessment (assessment of the environmental risks, energy consumption, and carbon emissions).
- Water resource analysis.

- Tailing characterization (characterization and content of historical tailings from the old exploitation, and analysis of the impact that future tailings of the process plant will generate has also been evaluated).
- Waste valorisation (valorisation solution of the proposed iron ore benefit tailings streams aiming to benefit its contained REEs by gravimetry while improving mining environmental footprint and circular economy).
- Mine operation optimisation.
- Mineral processing (development of the Basic Engineering and the Techno-economic Assessment for the process plant, including equipment, energy and process flow diagram).

E-LIX - The Atalaya/Lain Tech Pilot

The Atalaya/Lain Tech project (E-LIX) is based on a novel hydrometallurgical process for leaching Cu and Zn sulphides (chalcopyrite and sphalerite).

The E-LIX System is based on a new electrochemical process that extracts relevant metals from sulphide concentrates by means of singular catalyst under specific physicochemical conditions. Thus, the system puts copper and other metals into solution for subsequent recovery by precipitation or solvent extraction-electrowinning. This system is implemented as an industrial-scale plant (E-LIX Phase I Plant), and expected to unlock relevant polymetallic resources in Atalaya's Riotinto District, including strategic EU raw materials (Cu, Co and PGMs) and Zinc, by increasing recoveries from low-grade ores.

Additionally, through the I4-GREEN Open Call E-LIX is also focusing on:

- Design, processing, manufacturing and installation of the E-LIX water management system
- Firefighting (enhance customized fire detection, prevention and extinguishing capabilities for the E-LIX plant).
- Environmental Assessment (calculation of the E-LIX Project carbon and water footprint and its impact on other mineral processing technologies).
- Design, fabrication & installation of the solid-liquid separation by pressurized membrane filtration for an effluent zero discharge, working continuously in a closed circuit.
- Ad-hoc design for the sedimentation and clarification system. Mainly from the piping and instrumentation design and fluid transportation.

5. Environmental Impacts of Mine Waste Valorisation in the I4-GREEN Regions

The implementation of mine waste valorisation techniques in the regions of Andalucía, Castilla y León, Extremadura, and Alentejo can significantly mitigate environmental impacts. Across these regions, mine waste valorisation offers (1) Reduced Environmental Footprint: Lower waste volumes translate into reduced need for land for waste disposal, decreasing the impact on local landscapes and ecosystems; (2) Enhanced Ecosystem Protection: By controlling pollution from mine waste, these techniques help protect local flora and fauna, contributing to biodiversity conservation; (3) Support for Sustainable Practices: Increasing resource efficiency supports sustainable mining practices, aligns with global environmental goals, and promotes social acceptance of mining activities.

We include a detailed overview of these impacts for each region (table 1):

	Reduction in Waste Volume	Pollution Control	Resource Efficiency
Andalucía	By employing waste valorisation techniques such as recovering metals through bioleaching and phytomining, Andalucía can reduce the waste volumes from its extensive mining operations, particularly in the Iberian Pyrite Belt.	The region's sulphide-rich waste can be a source of acid mine drainage (AMD). Valorisation techniques that stabilize these wastes or recover valuable components help in mitigating AMD by reducing the exposure of sulfidic materials to environmental factors that trigger oxidation.	The use of waste as a resource reduces the demand for virgin materials and decreases the environmental footprint associated with extracting and processing these new resources. Exploitation of CRMs and strategic minerals from mining wastes is a way to increase circularity, as well as an opportunity to supply the markets for these elements.
Castilla y León	With the phasing out of coal mining, the focus has shifted to managing existing waste. Re-purposing mine waste for construction or landscape restoration can help reduce on-site waste volumes, aiding in land reclamation efforts.	Techniques like phytostabilization are particularly relevant here, where historical coal mining has sometimes had a pollution impact. These methods can help reduce the mobility of heavy metals, preventing contamination of water sources.	The extraction of remaining valuable minerals from old mine tailings or dumps through techniques like bioleaching increases the overall resource efficiency, ensuring that less of the extracted material is wasted.
Extremadura	As lithium becomes increasingly important due to the Green Transition, implementing advanced extraction techniques like solvent extraction and electrowinning in lithium mining can maximize recovery rates and minimize waste.	Managing waste from lithium extraction processes is crucial to prevent chemical leachates from contaminating local ecosystems. Using waste in construction materials can help encapsulate harmful elements, reducing their environmental impact.	Efficient processing techniques ensure that the maximum amount of lithium is extracted from each ton of mined ore.
Alentejo	Valorisation strategies, including the recovery of additional copper and zinc from tailings, can reduce waste volumes (e.g., from the Neves-Corvo mine) and extend the life of existing tailings dams. The same can be applied to closed and abandoned mine tailings.	Phytoremediation techniques can be applied to manage and stabilize mine waste, reducing the leaching of toxic metals into the environment and helping remediate already impacted areas.	Recycling mine waste not only provides materials for local industries, such as construction, but also reduces the need for new mining endeavours, thereby conserving resources and energy.

Table 1: Environmental Impacts of MWV in the I4-GREEN project regions

In the I4-GREEN regions, the environmental impact of MWV is mainly three-fold, and interlinked. Mine waste valorisation directly impacts on resource efficiency, which leads in a degree to a reduction in waste volume. This, in its turn, leads to a minimization of any possible pollution impacts through the extraction of what are valuable but potentially hazardous materials in some cases.

These valorisation efforts not only contribute to environmental sustainability but also align with broader economic and social goals, creating a more favourable outlook for the mining industry in these regions.

6. Socioeconomic Impacts of Mine Waste Valorisation in the I4-GREEN Regions

Mine waste valorisation techniques can significantly influence socioeconomic landscapes in regions such as Andalucía, Castilla y León, Extremadura, and Alentejo. These impacts often manifest in terms of job creation (new roles in waste processing and technology maintenance), economic gains (revenue from recovered metals and savings on waste management), and positive community effects (improved health and safety standards in local communities.). We include a description of how each I4-GREEN ecosystem region can potentially be affected (table 2).

	Job creation	Economic Gains	Community Effects
Andalucía	The adoption of advanced mine waste valorisation processes such as bioleaching from mine tailings can create new employment opportunities in Andalucía. These jobs may be in areas like operation and maintenance of new plant facilities, waste processing, and environmental monitoring.	Utilizing mine waste as a resource can open new revenue streams in the region of Andalucía (e.g., selling recovered metals from tailings). Additionally, the region might see reduced costs associated with waste management and land reclamation.	Reducing the environmental footprint of abandoned historic mine waste can improve their possible impact on the health of local populations by reducing exposure to harmful pollutants. Also, community relationships can improve as mining firms invest in sustainable practices, enhancing their social license to operate.
Castilla y León	As coal mines in Castilla y León close, reclamation and valorisation projects could provide alternative employment for those who previously worked in the mining sector. This might include roles in managing phytoremediation projects or operating facilities that convert waste to useful products.	Economic revitalization through mine waste valorisation could offset some of the economic downturn caused by the decline of traditional mining. The development of new technologies and processes for mine waste management may attract investment and foster innovation in related sectors.	Environmental improvements and new employment opportunities can stabilize local economies and prevent the out-migration of residents, contributing to sustained community vitality.
Extremadura	The exploration and development of lithium resources, and the application of cutting-edge valorisation techniques, could lead to job creation in both mining and related technology sectors. This includes jobs in extraction, processing, environmental management, and R&D.	With the increasing demand for lithium, particularly for use in electric vehicle batteries, effective valorisation and increased resource efficiency could place Extremadura at the forefront of a growing market, potentially leading to significant economic expansion.	As mining activities can sometimes lead to displacement or environmental degradation, effective waste valorisation could mitigate these effects, thereby supporting local consent and fostering a more positive perception of mining projects.
Alentejo	Given the intensive mining activities, particularly in copper and zinc extraction in the Portuguese side of the Iberian pyrite-belt, valorisation techniques like phytomining and bioleaching could create specialized jobs in biotechnology and environmental science. Exploration and revaluation of abandoned and closed mines or deposits would create specialized jobs.	By extracting additional value from waste, mines can increase their operational efficiency and profitability. This could lead to broader economic benefits, including increased tax revenues and funding for local services.	Successful mine waste projects can enhance environmental quality, which can lead to better public health and improved living conditions. Also, these projects often require collaboration with local universities and institutions, thereby enhancing local education and technical skills

Table 2: Socioeconomic Impacts of MWV in the I4-GREEN project regions

The main socioeconomic impact of MWV in the I4-GREEN regions could be identified as the job creation opportunities. Although some mines close due to the reduction in use of its exploitable resource (i.e., coal), other job opportunities rise in relation to more modern technologies used for MWV: the implementation of valorisation techniques often requires skilled personnel, fostering local education and training opportunities.

Moreover, mine waste valorisation opens the opportunity of economic gains in those locations with historical mine sites and waste. The valorisation of mine waste can offer economic profit to the regions, as well as a positive social assessment impact through the reduction of the risk of possible environmental impacts.

Overall, the socioeconomic impacts of mine waste valorisation in these regions are broadly positive, driving not just environmental sustainability but also economic and social benefits. However, the success of these initiatives often depends on consistent policy support, community engagement, and ongoing investment in technology and workforce development.

7. Challenges and limitations

Deploying state-of-the-art mine waste valorisation techniques presents several challenges and limitations across technical, economic, and regulatory domains. These hurdles can affect the feasibility, efficiency, and scalability of valorisation projects. Here's a detailed look at these challenges:

Technical Challenges

- <u>Complexity and variety of Waste Composition</u>: Mine waste often contains a complex mix of minerals (on some occasions, from the mixture of wastes from different origins), chemical substances, and metals, some of which may interfere with recovery processes for others. Developing technologies that can efficiently handle such diversity is challenging.
- <u>Scale of Operation</u>: Scaling up laboratory-proven techniques to industrial levels can be difficult. The processes that work well on a small scale may not necessarily be effective or efficient when expanded due to increased variability and logistical complications.
- <u>Technological Limitations</u>: Some advanced valorisation techniques may still be in the developmental or experimental stages and not yet fully proven in diverse operational environments. Integrating these technologies into existing mining operations can also be technically demanding.
- <u>Environmental Controls</u>: Technologies must not only be effective in recovering resources but also environmentally benign. For instance, bioleaching must be managed to avoid unintended release of toxic substances into the environment.

Economic Barriers

- <u>High Capital Investment</u>: State-of-the-art valorisation technologies often require significant upfront investment in terms of equipment, infrastructure, and technology development. The capital cost can be prohibitive, particularly for smaller mining operations or in regions with limited financial resources.
- <u>Cost-Effectiveness</u>: The economic viability of recovering certain elements from mine waste can be marginal, especially if the market prices are volatile or if the concentration of valuable materials in waste is low or in a remote location. The process needs to be cost-effective relative to the value of recovered materials.
- <u>Return on Investment (ROI)</u>: The long-term nature of ROI from valorisation technologies can deter investment, as benefits might accrue only over extended periods, making them less attractive in environments where quick returns are favoured.
- <u>Market Dependencies</u>: The success of valorisation also heavily relies on market demand for recovered materials. Fluctuations in commodity prices can significantly impact the financial sustainability of valorisation projects.

- Remote Location: If far from the processing location, the economic feasibility of the operation can be impacted.

Regulatory Issues

- Environmental Regulations: Compliance with stringent environmental regulations can be challenging. New technologies must undergo thorough environmental impact assessments, which can be time-consuming and complex. The process to obtain necessary permits and approvals can delay project implementation. In Spain, restoration mining site during and at the end of an exploitation is mandatory according to the Spanish Mining Act. This limits the life span for the wastes' valorisation. Additionally, depending on the type of restoration, the possibility of a future valorisation of the waste can be limited.
- Cross-Border Regulatory Variations: For multinational mining companies, differences in regulatory frameworks across countries can complicate the deployment of uniform valorisation technologies. Adapting to each region's regulatory demands requires additional resources and planning.
- Technology Approval: New and emerging technologies might not be immediately recognized or regulated under existing frameworks, leading to uncertainties in legal and compliance aspects. Gaining regulatory approval for innovative processes can be a lengthy and uncertain process.
- Waste Classification: In some jurisdictions, mine waste may be classified as hazardous, imposing additional handling, treatment, and disposal requirements that can limit the options for valorisation.
- By-product authorization process: Waste regulation makes difficult the process to qualify a specific waste as by-product that can be used in other activities, usually industry.

Successfully addressing these challenges requires a multi-faceted approach, which I4-GREEN fully tackles through its activities:

- Research and Development: Continuous investment in R&D can help improve the efficiency, effectiveness, and environmental compatibility of valorisation technologies.
- Stakeholder Engagement: Collaborating with government bodies, local communities, and industry experts can help align project goals with regulatory requirements and social expectations.
- Economic Incentives: Financial incentives such as tax breaks, subsidies, or grants can encourage investment in waste valorisation technologies.
- Pilot Projects: Implementing pilot projects can help demonstrate the viability and benefits of valorisation technologies, paving the way for larger-scale adoption.

By overcoming these challenges, the mining industry can enhance its sustainability practices, turning waste into a resource and significantly reducing the environmental footprint of mining activities.

8. Future trends and innovations

The valorisation of tailings is aligned with the United Nations' Sustainable Development Goals (SDGs). Mine tailings mining can contribute especially to the SDG11 "Sustainable Cities and Communities" and to the SDG12 "Responsible Consumption and Production" by minimizing the output of waste. The future of mine waste valorisation is poised for significant advancement driven by technological innovation, evolving policy and regulatory frameworks, and changing market dynamics. These factors collectively shape the potential for turning mine waste into valuable resources, thus enhancing the sustainability of the mining industry. Here's an exploration of these future trends and innovations:

Technological Advances

- Nanotechnology: The use of nanotechnology in mine waste valorisation can lead to more efficient recovery methods. Nano-enhanced materials could potentially alter the physical and chemical properties of mine waste, allowing for the extraction of trace amounts of valuable metals and minerals.

- Biotechnology: Advances in biotechnology, including genetically engineered microorganisms, offer promising ways to enhance bioleaching and phytomining processes. These organisms can be tailored to tolerate higher concentrations of metals or to process specific minerals more efficiently.
- Automation and AI: The integration of automation, artificial intelligence, and machine learning in mine waste processing can optimize operations, reduce costs, and improve safety. AI could predict the recovery rates of different processes and adjust operations in real-time for maximum efficiency.
- Advanced Materials: Development of new materials that can enhance the durability and efficiency of processing equipment, or that can be produced directly from mine waste (such as advanced ceramics or composites), is likely to increase.

Policy and Regulation Changes

- Stricter Environmental Standards: As global awareness of environmental issues grows, stricter regulations are likely to be implemented concerning waste management and recycling. These will require more efficient and environmentally friendly valorisation technologies.
- Incentives for Sustainable Practices: Governments might introduce more incentives to promote circular economy practices within the mining industry, such as tax breaks, grants, or subsidies for companies that invest in waste valorisation.
- Global Cooperation on Mining Standards: There may be increased international cooperation to standardize regulations on mine waste management, aiming to reduce the global environmental impact of mining activities and to promote sustainable practices universally.

Market Dynamics

- Increasing Demand for Critical Minerals: With the growth in technologies such as electric vehicles, renewable energy systems, and electronics, there is an increasing demand for rare and critical minerals. This trend can make the valorisation of mine waste more economically attractive, as even low-grade waste may become a viable source of these materials.
- Volatility in Commodity Prices: Fluctuations in commodity prices can greatly influence the profitability of mine waste valorisation. Higher prices can justify the cost of extracting valuable materials from waste, whereas lower prices may reduce the financial viability of these processes.
- Corporate Responsibility and ESG: Environmental, Social, and Governance (ESG) factors are becoming critical in investors' decision-making processes. Companies adopting sustainable waste management and valorisation techniques may benefit from enhanced investor interest and better market reputation.

Integration of Valorisation in Mining Operations

- Holistic Waste Management Strategies: Future mining operations could be designed with integrated waste valorisation processes from the outset, rather than treating waste valorisation as an afterthought. This approach would make operations more sustainable and economically efficient.
- Cross-Industry Collaboration: Collaborations between the mining industry and other sectors (such as construction and chemical manufacturing) could open new avenues for using mine waste in diverse applications, further driving the development of valorisation technologies.

As these trends develop, the mining industry's approach to waste management is expected to undergo significant transformation. Innovations in technology will play a key role, supported by conducive policy environments and responsive market dynamics. Together, these factors will push the industry towards more sustainable practices, turning mine waste into a resource rather than a liability.

9. Conclusions

Europe is working towards a greater independence of CRM supply through a three-fold strategy: a more responsible supply from third countries, a greater exploitation of CRMs within Europe and a reuse or recycling of secondary CRMs. There is a pressing need for continued innovation and adoption of mine waste valorisation methods. These efforts will help align the mining industry with global sustainability goals, providing environmental benefits while also enhancing profitability and community relations. Such developments are essential for fostering a more circular economy in which resource use is optimized, and environmental impacts are minimized, benefiting both the industry and broader society.

The I4-GREEN project remains committed to fostering innovation and collaboration in mine waste valorisation, ensuring that environmental and socio-economic benefits are maximized for the communities and regions involved.

The deliverable underscores the importance of advancing mine waste valorisation technologies to achieve environmental sustainability and socio-economic development.

By providing a state-of-the-art overview and an analysis of the regional environmental and socioeconomic impacts, this report lays the groundwork for regional investment and the replication of successful practices across the EU. The findings and insights related to the regional aspects will support policymakers, industry leaders, and investors in driving forward the agenda of sustainable mining and resource efficiency.

10. References & Resources

- Deloitte – Navigating global challenges and opportunities in mining and metals – Tracking the trends 2024
- Deloitte - The indispensable role of mining and metals - Tracking the trends 2023
- European Commission – Waste Framework Directive
- Global Mining Waste Management Market Report by Mining Type, Mineral/Metal, Waste Type, and Region 2024-2032.
- IGME. Panorama Minero 2022 (datos de 2021).
- IISD – How to Advance Sustainable Mining
- International Council on Mining and Metals (ICMM) – Tailings and Waste Management
- Kinnunen & Kaksonen (2019). Towards circular economy in mining: opportunities and bottlenecks for tailings valorisation. https://doi.org/10.1016/j.jclepro.2019.04.171
- Market Research Future – Mining Waste Management Market Size, Share & Trends Analysis Report By Mining Method (Surface Mining, Underground Mining), By Metal/Mineral (Thermal Coal, Coking Coal, Iron Ore, Gold, Copper, Lead, Zinc), By Waste Type, By Region, And Segment Forecasts, 2024 - 2030
- Leistel et al (1998) The volcanic-hosted massive sulphide deposits of the Iberian Pyrite Belt Review and preface to the Thematic Issue Miner. Deposita, 33 (1) (1998), pp. 2-30, 10.1007/s001260050130
- Pinedo-Vara et al. (2008) Piritas de Huelva: su historia, minería y aprovechamiento. Suc. de Rivadeneyra.
- Rio Tinto. (2020). Tailings Management. https://www.riotinto.com/en/sustainability/environment/tailings
- Rosario-Beltré et al. (2023) Critical Raw Materials recovery potential from Spanish mine wastes: A national-scale preliminary assessment. ScienceDirect https://doi.org/10.1016/j.jclepro.2023.137163
- OECD. (2019). The Circular Economy in Mining and Metals. https://www.oecd.org/en/topics/environment.html

- UNEP. (2020). Mineral Resource Governance in the 21st Century. https://www.unep.org/resources/report/mineral-resource-governance-21st-century
- United Nations Environment Programme (UNEP) – Mineral Resource Governance
- World Economic Forum – Mining and Metals in a Sustainable World