# I4-GREEN
# (Mine waste Database and Report on interregional mine sites)
# D6.7
# 15/01/2025

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| General information | | | | |
|---|---|---|---|---|
| Work Package | WP6 | | | |
| Deliverable | D6.7 Mine waste Database and Report on interregional mine sites | | | |
| Due Data | M24 31st October 2024 | | | |
| Submission Date | M27 15th January 2025 | | | |
| Deliverable Lead | JdA-SGIM | | | |
| Dissemination Level | X | Public (PU) | | Confidential (CO) |
| Document Nature | | Report (R) | X | Data sets, microdata, etc (DATA) |
| 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<br><br>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.<br><br>In the light of the new, innovative technologies to be developed within I4-GREEN, special attention will be given to exploration and processing technologies (e.g. mine waste mapping, sampling, modelling, design / processing). The following characteristics will be described in each participant region of objective: a) Mine wastes Country Directive/law requirements; b) Mining industry – overall description (productivity value, employment); c) Main minerals and mining wastes (quantification and possible value); d) Current exploration and processing technologies e) Previous national and EU mine waste recovery projects. This information will be shared with interregional authorities, DG REGIO, DG GROW and EU projects working in the area. | | | |
| Authors | JdA-SGIM | | | |
| Reviewers | ICAMCYL, ACPMR | | | |
| Status | | Draft | X | Final |

| Revision History | | | | |
|---|---|---|---|---|
| Version | Date | Author | Organisation | Status |
| V1 | 26/12/2024 | MVM, AFA, JPG | JdA-SGIM | Draft |
| V2 | 02/01/2025 | AGG, RC | ICAMCYL | Draft |
| V3 | 06/01/2025 | Giulia Resta, Luís Martins | ACPMR | Draft |
| V4 | 14/01/2025 | MVM, AFA, JPG | JdA-SGIM | Final |

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| Glossary | |
|---|---|
| Acronym | Meaning |
| BAT | Best Available Techniques |
| CRMs | Critical Raw Materials |
| KMZ | Keyhole Markup language Zipped |
| OP | Open Pit |
| PP | Mineral Processing Plants |
| UG | Underground |
| WMP | Waste Management plan |

# 1. Executive summary

This document support the Data provided in "Mine waste Database and Report on interregional mine sites", presenting the outcomes of the I4-GREEN project in addressing the critical issue of mine waste management and valorization across targeted regions in Portugal (Alentejo) and Spain (Andalucía, Castilla y León, and Extremadura). It aims to support sustainable mining practices while unlocking economic potential from mining wastes, aligning with EU directives and regional investment strategies.

## 1.1. Introduction and Objectives

This document establishes a comprehensive framework to evaluate and valorize mining wastes in selected regions. Its objectives include:

- Analyzing existing data (and lack of data). Collecting and integrating valuable data from various sources into a centralized database.
- Analyzing waste composition and identifying valuable elements for recovery.
- Estimating potential revenues from reprocessing mine waste.
- Proposing sustainable strategies for mining waste valorization.

The study emphasizes the complexity of mine waste management, requiring an interdisciplinary approach that integrates environmental, technical, and economic factors.

## 1.2. Mine Waste Country Regulation. Directives and Requirements

### Portugal (Decreto-Lei n.º 10/2010)

Portugal's regulatory framework aligns with EU Directive 2006/21/CE [23], it focuses on safe waste management, accident prevention, and public participation. The key aspects include:

- Mandatory waste management plans (WMPs) emphasizing prevention, reuse, and safe disposal.
- Strict licensing, oversight, and financial guarantees for rehabilitation.
- A focus on minimizing environmental impacts through the best available techniques (BAT).

An active actor that supports mining waste management in Portugal is the Empresa de Desenvolvimento Mineiro (EDM), which focuses on environmental rehabilitation resource management and support for the national mining sector. Under Decreto-Lei nº 198-A/2001 (establishes the concession regime to carry out environmental rehabilitation of degraded mining areas), EDM is responsible for addressing environmental liabilities in degraded mining areas, such as abandoned or pre-1990 deactivated sites, as defined in Line 2, Article 2 of the decree. This includes restoring soils and water resources, reducing health risks and promoting sustainable waste management aligned with EU policies. Additionally, EDM conducts studies to ensure safe treatment or repurposing of mining waste. As a new challenge, EDM imposed on itself the objective of using mining waste and water as secondary sources of raw mineral materials by applying more effective mobilisation and reprocessing of mining residues.

### Spain (RD 975/2009)

Spain's Royal Decree aligns with EU Directive 2006/21/EC [23], addressing the sustainable management of extractive industry waste. It prioritizes:

- Environmental protection and human health.

- Comprehensive restoration plans for mining sites.
- Strict classifications for waste facilities based on risk levels, ensuring long-term safety and monitoring.

## 1.3. Mining Industry Overview

### Portugal

Portugal is a prominent European producer of copper, zinc, and tungsten, with emerging potential in lithium extraction in the Norte and Centro regions. Over the decades, modernization and stricter regulations have significantly improved productivity and environmental standards. Mines like Neves-Corvo and Aljustrel, both in Alentejo, exemplify technological and operational advancements.

The Iberian Pyrite Belt is the most important mine province in Portugal, it is renowned for its massive sulphide deposits which are particularly rich in copper zinc, lead, and to a lesser extent, gold and silver. Historically, these deposits have been exploited for their non-ferrous metal content, making this one of the principal mining areas in Europe.

Portugal is strong in producing industrial minerals such as clays and feldspars used in ceramics and other construction materials. These resources are especially abundant in the Centro region where high-quality clays can be found.

The country is also famed by its dimension stones from Alentejo for its 'Marble Triangle', encompassing the areas of Estremoz, Vila Viçosa, and Borba. Renowned for its exceptional quality and beauty, it is widely present in national and international markets.

Additionally, granite (mainly from the Norte region), limestone (mainly from the Centro region) and marble (mainly from Alentejo and Centro) play a significant role in the country's mineral resources industry.

### Spain: Andalucía, Castilla y León, and Extremadura

- Andalucía: The Iberian Pyrite Belt, home to the Rio Tinto, Cobre Las Cruces and Aguas Teñidas mines, is a key resource for copper, zinc, and lead. It is also the first producer of strontium in Europe. Advances in automation and sustainability have transformed mining in this region.
- Castilla y León: Known for gold, tungsten, feldspar and slate mining, this region has shifted focus from traditional resources to high-value industrial minerals.
- Extremadura: An emerging mining region, Extremadura's lithium and tin deposits are central to Europe's green energy transition. It is also the main producer of Feldspar.

## 1.4. Employment and Safety

### Portugal

The mining sector has undergone significant transformations, with marked improvements in employment conditions and workplace safety. Accident rates have declined by over 70% since the 1980s, driven by:

- Regulatory reforms enforcing safety measures.
- Advanced technologies reducing direct exposure to hazardous environments.
- A proactive safety culture promoting risk management and prevention.

### Spain: Andalucía, Castilla y León, and Extremadura

These regions have mirrored Portugal's progress in workplace safety and employment. Investments in automation and stricter oversight have contributed to near-zero fatality rates in recent years.

Ongoing initiatives to enhance gender diversity and technical training programs further improve workforce conditions.

## 1.5. Main Minerals and Mining Wastes

This document identifies key minerals and their associated waste:

- Critical Raw Materials (CRMs): Include, among others, copper, feldspar, fluorspar, strontium, arsenic, antimony, bismuth, magnesium, manganese, tungsten, baryte, lithium, cobalt, and rare earth elements, essential for renewable energy and digital technologies.
- Additional Valuable Elements: Gold, silver, industrial minerals like silica and gypsum and natural stone like marble or slate, are highlighted for their economic potential.

We have been able to verify that data availability is not enough to make a global analysis and get definitive conclusions. Until now, the objective of mining waste inventories is to define the potential of environmental damage of each deposit and the need of a restoration actuation on them but not to determine the mineral and economic potential (CRMs).

After a deep investigation with the main responsible authorities in the countries and regions involved in this project, only Andalucía have provided quantity and quality of information enough to estimate the potentiality of mining waste deposits in the region.

Data integration across regions has revealed:

- A wealth of mining wastes with varying compositions and physical forms (tailings, waste rocks, and wastewater).
- Opportunities for reprocessing these wastes to recover valuable substances.

## 1.6. Processing Mining Wastes: Key Considerations

The processing of mining waste depends on several factors:

- Physical Form: Technologies vary for wastewater, tailings, or solid waste.
- Chemical Composition: The presence of valuable metals or hazardous substances influences the economic viability of recovery efforts.
- Environmental Impact: Compliance with regulations ensures sustainability and minimizes ecological risks.
- Economic Feasibility: Market demand and commodity prices are critical determinants of profitability.
- Infrastructure and Logistics: Dispersion of waste deposits and connectivity between them. Proximity to processing facilities and transportation networks affects operational efficiency.

## 1.7. Market Prices and Potential Revenues

Market prices for CRMs and additional elements guide recovery strategies:

- CRMs such as lithium and cobalt command high prices, supporting their recovery from mine waste.
- Precious metals like gold and silver, although not CRMs, present significant economic value.

This report estimates potential revenues by analyzing the composition of mine wastes and aligning them with market trends.

## 1.8. Clustering and Data Management

Advanced clustering techniques are used to group mine waste sites based on geographic and compositional attributes. These methods support:

- Identifying high-potential areas for investment.
- Developing tailored recovery strategies for specific waste types.

## 1.9. Conclusions

This report provides a robust framework for integrating data, analyzing mining wastes, and proposing valorization strategies. Key takeaways include:

- The potential of mine waste as a resource base for critical and valuable elements.
- The lack of information and the need to implement extensive exploration campaigns to better understand the potentiality of mining wastes for CRMs exploitation.
- The importance of regulatory compliance and sustainability in mining waste management.
- The need for continued investment in technologies and infrastructure to support waste reprocessing.

The findings align with EU sustainability goals and offer actionable insights for regional investment in mining waste valorization.

# 2. Introduction and objectives

## 2.1. Introduction

According to task (T6.5 Development of database on mine waste and state of the art study on valorisation technologies for regional) a report on the different technologies for mine waste valorisation and a report on I4-GREEN interregional mine sites were defined. The following characteristics were described in each participant region of objective:

a) Mine wastes Country Directive/law requirements.
b) Mining industry – overall description (productivity value, employment).
c) Main minerals and mining wastes (quantification and possible value).
d) Current exploitation and processing technologies.
e) Previous national and EU min waste recovery projects.

This report includes such information, with a special focus on the Target c). This task has been faced by first gathering data from previously existent databases in the targeted regions of I4-GREEN. Afterwards, such data has been exploited by following the procedure described below in this document, in order to get the most valuable results for the project and propose further ways of improving this task in the future.

It is especially important to consider the inherent complexity of this task, since the valorization of a mine deposit usually requires intensive works for its characterization, the overall permitting phase and preparation of mine exploitation, ore handling, technological availability and environmental restoration plans.

## 2.2. Objectives of this deliverable

The preliminary objectives set for this task are the following:

a. Gather the existent data in the different locations covered by the project.

b. Analyze and integrate the data into a single database, considering its inherent heterogeneity.

c. Perform calculations for the most relevant element and/or substances of economic interest, where data are available.

d. Build a clustering strategy in order to identify areas of special interest in terms of geographical location and the different types of mining wastes.

e. Evaluate the potential valorization of the mining waste according to the present market prices.

f. Estimate the potential recovery and revenues in case of implementation of waste recovery plants.

g. Propose new lines of future advances of this research.

# 3. Mine waste country directive/law requirements

## 3.1. Portugal (Decreto-Lei n.º 10/2010)

Decreto-Lei n.º 10/2010 [2] establishes the legal framework for the management of waste resulting from mineral extraction and quarrying activities. This legislation transposes the European Union's Directive 2006/21/EC [23] into Portuguese law, aiming to address the environmental, public health, and safety challenges posed by the mining and quarrying industries. The decree highlights the specificities of mining waste, which often consists of large volumes and has potential for significant environmental and human health risks if improperly managed.

### Objectives

The decree aims to ensure that extraction waste is managed to prevent or reduce adverse environmental and health impacts. Its key objectives include:

1. Administrative Simplification: The decree seeks to minimize bureaucratic burdens by integrating waste management requirements into existing licensing processes.
2. Safe Waste Management Practices: The adoption of a waste management plan (WMP) is required, which outlines measures for prevention, reuse, and environmentally sound disposal of mining waste.
3. Licensing and Oversight: Specific procedures for licensing extraction waste facilities are established, ensuring compliance with safety and environmental standards.
4. Prevention of Major Accidents: The legislation incorporates measures to mitigate risks associated with hazardous substances in waste facilities.
5. Public Participation and Transparency: The decree promotes the involvement of the public in the decision-making process, particularly in licensing procedures and in cases involving potential transboundary impacts.

### Scope of Application

The decree applies to the management of waste generated from the prospecting, extraction, treatment, and storage of mineral resources, including operations in quarries. However, certain exclusions are specified:

- Waste not directly resulting from these operations.
- Offshore mining waste.
- Re-injection of pumped water as defined under other specific Portuguese laws.

Additionally, the decree extends to abandoned mining sites integrated into recovery plans approved under prior legislation.

## Key Provisions

Waste Management Principles

1. Prevention and Reduction: Operators must minimize waste generation and its hazardous characteristics. Techniques should prioritize methods that have no significant environmental impact.
2. Sustainability: Waste management must adhere to the best available techniques (BAT), tailored to the geographical and environmental conditions of the site.
3. Prohibition of Uncontrolled Disposal: The decree strictly prohibits abandoning or uncontrolled dumping of mining waste.

Licensing and Planning

Operators are required to develop a detailed Waste Management Plan (WMP), which must include:

- Classification of waste facilities based on risk (e.g., Category A for higher-risk facilities).
- Characteristics of the waste and estimates of quantities produced.
- Environmental and health risk assessments.
- Post-closure plans, including site rehabilitation and monitoring.
- Measures to prevent groundwater contamination and reduce air pollution.

The WMP must be reviewed every five years and revised in case of significant operational changes.

## Facility Construction, Operation, and Closure

1. Site Selection: Waste facilities must be located considering geological, hydrological, and seismic conditions.
2. Operational Requirements: Regular monitoring and inspections must ensure stability and prevent environmental damage. Operators must promptly report incidents that affect stability or cause significant environmental harm.
3. Closure Plans: A comprehensive closure plan is mandatory, including long-term maintenance and environmental monitoring. Closure requires a final inspection and approval by the relevant licensing authority.
4. Financial Guarantees: Operators must provide financial guarantees to cover the cost of rehabilitation and post-closure monitoring.

## Accident Prevention and Emergency Response

Facilities classified as Category A must implement measures aligned with the prevention of major accidents involving hazardous substances. This includes:

- Development of an internal emergency plan by the operator.
- Coordination with external emergency services for off-site response plans.
- Regular testing and updates of emergency procedures.

In case of accidents, operators are required to activate their emergency plans and notify authorities within 48 hours. Transboundary impacts must be communicated to affected EU Member States.

## Public and Transboundary Participation

The decree underscores the importance of public engagement by requiring:

- Public access to information on waste management plans and facility operations.
- Public consultation during licensing processes, with responses integrated into final decisions.
- Collaboration with EU Member States for facilities with transboundary environmental risks.

## Compliance and Enforcement

The decree mandates periodic inspections and monitoring by licensing authorities to ensure compliance with established standards. Operators must submit annual monitoring reports detailing:

- Waste characteristics and volumes.
- Environmental monitoring results.
- Compliance with the WMP and licensing conditions.

Non-compliance may lead to penalties, including suspension of operations or revocation of licenses.

## Strategic Implications

By implementing Decreto-Lei n.º 10/2010, Portugal aligns with EU directives on sustainable mining practices. This legislative framework facilitates the integration of environmental protection with economic activities in the mining sector. It promotes resource efficiency, reduces risks to communities, and ensures long-term site rehabilitation.

## Conclusion

Decreto-Lei n.º 10/2010 provides a robust framework for the environmentally responsible management of mining waste. Through its comprehensive measures, it addresses both immediate and long-term challenges associated with waste from mineral extraction. This legal instrument is a critical step toward achieving sustainability in the mining industry, ensuring protection for the environment and public health while supporting economic development.

# 3.2. Spain (RD 975/2009)

The Royal Decree 975/2009, (see [3]), approved on June 12th 2009, establishes regulations for managing waste from the extractive industries in Spain, with specific measures for rehabilitating areas impacted by mining activities. It integrates the Directive 2006/21/EC [23] of the European Union into Spanish law and strengthens existing frameworks for environmental protection and sustainable practices in mining.

## Objectives

1. Environmental Protection: To prevent or reduce adverse effects on the environment, including soil, water, air, and biodiversity.
2. Human Health: To minimize health risks associated with mining activities and waste management.
3. Waste Management: To promote efficient, sustainable, and safe handling of mining waste, including recycling and reuse where feasible.
4. Area Rehabilitation: To ensure comprehensive rehabilitation of affected areas, restoring their ecological and economic functions.

## Scope of Application

The decree applies to:

- Mining Activities: Exploration, extraction, treatment, and storage of mineral resources.
- Waste Facilities: Any site for storing or depositing mining waste, including tailings ponds and waste heaps.

Excluded:

- Submarine mining activities.
- Specific reinjection of water under controlled conditions.

## Key Provisions

1. Restoration Plans

Operators must develop a Restoration Plan as part of obtaining mining authorizations. This plan includes:

- A description of the affected environment.
- Proposed measures for site rehabilitation.
- Waste management strategies.
- A timeline and budget for rehabilitation efforts.

2. Waste Management Plans

Each plan must:

- Prioritize waste reduction, reuse, and safe disposal.
- Address potential environmental and health risks.
- Include specific designs for waste facilities based on geotechnical, hydrological, and seismic studies.

3. Licensing and Public Participation

- Mining operations must obtain specific licenses for waste management, including environmental impact assessments.
- Public consultations are required for high-impact projects to ensure community involvement.

4. Financial Guarantees

Operators are required to provide financial guarantees to cover:

- Site rehabilitation costs.
- Long-term monitoring and maintenance of waste facilities.

## Waste Facility Classification

Facilities are classified into categories based on:

- Environmental Risks: Higher-risk facilities (Category A) require stringent safety and management protocols.
- Waste Type: Hazardous, non-hazardous, or inert waste.

## Environmental Safeguards

- Water Protection: Waste facilities must prevent groundwater and surface water contamination through containment systems and leachate management.
- Air Quality: Measures must be taken to minimize dust and airborne pollutants.
- Soil Integrity: Sites must be monitored for potential degradation, with restoration measures in place post-mining.

## Accident Prevention

High-risk facilities must:

- Implement risk prevention policies for major accidents.
- Maintain safety management systems and emergency response plans.
- Provide information to local communities on safety measures.

## Post-Closure Responsibilities

Once mining activities cease:

- Operators remain responsible for monitoring and maintaining the site to prevent residual environmental impacts.
- Financial provisions must ensure compliance with long-term obligations, including stability and water quality monitoring.

### Alignment with EU Directives

The decree incorporates EU guidelines on waste management, aligning with the goals of the Directive 2006/21/EC [23]. It ensures a consistent framework across member states for managing mining waste and rehabilitating affected areas.

### Enforcement and Sanctions

- Authorities conduct inspections to ensure compliance with licensing conditions.
- Non-compliance can result in penalties under Spain's Environmental Liability Law.

### Conclusion

RD 975/2009 provides a robust regulatory framework for managing mining waste in Spain. By emphasizing prevention, sustainability, and stakeholder engagement, it ensures that extractive activities align with modern environmental and social standards. This regulation not only protects natural resources but also establishes a pathway for the rehabilitation of areas impacted by mining, fostering long-term ecological and economic resilience.

# 4. Mining industry overall description

## 4.1. Production and Productivity Value in Portugal

Portugal has a long-standing history in mining, with significant developments over the past decades. Nowadays, the country plays a prominent role in the European mining sector, particularly in the extraction of metallic and industrial minerals. The Portuguese mining industry is characterized by modernized operations, sustainable practices, and a focus on strategic resources.

### Current Situation

Portugal is a leading European producer of copper, zinc, tungsten and marble. In Castro Verde, the Neves-Corvo mine plays a key role in the region's economy development. It is the 6º biggest producer of copper and the leading producer of zinc in Europe.

Tungsten production is also notable, with Panasqueira being a key global supplier. The country has seen rising demand for lithium, positioning Portugal as a major player in Europe's push toward energy transition and electric vehicle production. Active lithium exploration projects in Boticas, for example, are paving the way for future production.

### Evolution Over Decades

Mining productivity has evolved significantly due to technological advancements and stricter environmental regulations. In the 20th century, Portugal relied heavily on traditional extraction methods, with high environmental impacts. Since the 1990s, investment in automation, waste management, and energy efficiency has increased productivity and reduced ecological footprints.

### Key Minerals and Mines

Besides copper, zinc, and tungsten, Portugal is rich in feldspar, kaolin, and dimension stones such as marble and granite. These minerals support a vibrant export industry, particularly to European markets. Emerging projects in critical raw materials, including lithium and rare earth elements, highlight Portugal's potential to diversify its mining portfolio.

With robust resources and strategic initiatives, Portugal continues to position itself as a key player in sustainable mining in Europe.

## 4.2. Mining Production and Productivity in Spain: Andalucía, Castilla y León, and Extremadura

Spain has a geologically diverse territory and a wide range of mineral resources [14]. In 2021, the country produced roughly 3.8B€ worth of mineral products. Spain is an important producer of copper, zinc, strontium, tungsten, fluorspar, magnesite, and bentonite, among others. In 2021, it ranked as the fourth leading country worldwide in tungsten reserves, and the seventh in fluorspar and magnesite production. While the mining sector in Spain has suffered from several ups and downs in the past years, recently there has been a renewed interest in the sector in line with the European Union's need for critical minerals and an attempt to reduce its raw material dependency. With around 2610 active mines, employment reaches 17,000 people, showing a positive trend in the short and mid ranges.

On the other hand, Spain's regions of Andalucía, Castilla y León, and Extremadura are pivotal to the country's mining sector. They are rich in diverse mineral resources and have witnessed significant transformations in mining production and productivity over the decades.

### Andalucía

Andalucía is Spain's most important mining region, contributing significantly to national production. The Iberian Pyrite Belt, which spans across the province of Huelva and Sevilla, is a globally renowned mining area. It hosts some of Europe's largest deposits of polymetallic sulfides, particularly copper, zinc, and lead. The Cobre Las Cruces mine and the Aguas Teñidas mine exemplify state-of-the-art mining operations. These facilities employ advanced technologies to ensure high efficiency and sustainability. Atalaya Mining at the historic site of Riotinto restarted the operation in 2015 showing excellent possibilities for the following decades. Other projects are also carrying out their permitting processes in order to start operating during the next years.

In the past, Andalucía's mining sector relied on conventional methods with considerable environmental impact. However, since the 1990s, stringent EU directives and technological advances have revolutionized mining in the region. Productivity has surged through automation, and the emphasis on sustainability has reduced the ecological footprint.

The region also boasts significant reserves of iron ore and industrial minerals like strontium, feldspar, fluorspar, baryte and gypsum and marble, which support thriving construction and export industries. Recently, Andalucía has emerged as a hotspot for critical raw materials exploration, driven by Europe's energy transition goals.

### Castilla y León

Castilla y León is a historical mining region with a diverse resource base. The region is well known for its gold deposits, such as the Roman-era Las Médulas site.

The region was also an important producer of coal, although its relevance has declined due to the transition to cleaner energy sources. Tungsten is another significant mineral, with operations like the Barruecopardo mine in Salamanca contributing to global supply chains. Additionally, Castilla y León is a major producer of slate, feldspar, and magnesite, serving industrial and ornamental purposes.

Over the past decades, Castilla y León's mining sector has shifted focus from traditional resources like coal to high-value minerals and industrial raw materials. Investment in modern processing technologies and sustainability measures has increased productivity while preserving its natural heritage.

## Extremadura

Extremadura is an emerging mining region with substantial potential for critical raw materials, particularly lithium and tin. The region has seen growing interest in lithium exploration due to its strategic importance in battery production for electric vehicles. The Valdeflores and Cañaveral projects (Cáceres province) represent a significant initiative to position Extremadura as a European lithium hub.

Historically, the region's mining activity focused on metallic minerals like copper, iron, nickel, tin or tungsten, and phosphate minerals, which were key during the mid-20th century. While many traditional operations have ceased, modern exploration and advanced extraction technologies are revitalizing mining in Extremadura.

Recent figures include 178 active exploitations with a production of some 124 MEUR, with a direct employment close to 1900 people (see [12] for details).

The government and private sector have increasingly prioritized sustainability and local development, ensuring mining activities benefit surrounding communities. Extremadura also hosts vast deposits of granite and quartz, contributing to the ornamental stone market.

## Current Challenges and Future Prospects

The mining sectors in Andalucía, Castilla y León, and Extremadura share common challenges, including stricter environmental regulations, community concerns, and the need to adapt to technological innovations. However, these regions are poised to thrive by focusing on critical raw materials, aligning with global trends in renewable energy and technological development.

In summary, these three regions illustrate the dynamic evolution of Spain's mining industry, combining historical significance with modern innovation to meet current and future demands.

# 4.3. Employment and Accident Rates in Mining in Portugal

The mining sector in Portugal has undergone significant transformations over the last few decades, resulting in improvements in employment conditions, labor safety, and a marked reduction in workplace accidents. These advancements have been driven by regulatory reforms, technological innovation, and a growing commitment to aligning with EU safety and labor standards.

## Current Employment Landscape

Portugal's mining industry directly employs thousands of workers, with indirect employment contributing significantly to local economies in mining regions such as Alentejo, Norte, and Centro. The sector offers stable job opportunities, particularly in operations related to copper, zinc, tungsten, marble and lithium extraction and exploration. Emerging projects, like lithium mining to support the renewable energy transition, are expected to create additional employment, focusing on skilled labor for technologically advanced operations.

According to Direção Geral de Energia e Geologia (DGEG) (26), which is the national mining authority, the 2021 number of direct employment for the different extractive subsectors are:

- Industrial minerals: 810
- Construction minerals: 5,150
- Metallic ores: 2,272

A case of success is located in Alentejo, in Castro Verde municipality, the Neves-Corvo mine plays a key role in the region's economy development. It is the 6º biggest producer of copper and the leading producer of zinc in Europe. This mine employs approximately 1,300 in-house workers and 1,300 full-time contractors, contributing significantly to local employment. Furthermore, the mine operations have generated around 5,000 indirect jobs, amplifying its positive economic impact on the surrounding community. (27)

In recent years, industry has also seen an increase in initiatives aimed at fostering gender diversity and workforce training. Training programs supported by government and private enterprises have enhanced the technical skills of workers, preparing them for automated and environmentally conscious mining practices.

### Improvement in Working Conditions

Since the late 20th century, working conditions in the mining sector have improved considerably. Traditional labor-intensive and hazardous practices have been largely replaced by mechanized and automated systems, reducing direct exposure to dangerous environments. Compliance with EU regulations has mandated stricter oversight of workplace conditions, including better ventilation systems, protective gear, and standardized safety protocols.

The introduction of continuous training programs has also enhanced workforce competence, ensuring that employees can operate complex machinery safely while adapting to the latest technologies.

### Reduction in Accidents and Victims

Portugal has achieved remarkable progress in reducing accident rates in mining. Between the 1980s and today, fatal accidents and severe injuries have decreased significantly. This success stems from:

- Enhanced Safety Regulations: Implementation of EU Directives, such as the Framework Directive on Safety and Health at Work, has established stringent standards.
- Modern Technologies: Automated machinery has reduced direct human involvement in high-risk activities.
- Safety Culture: A shift towards proactive risk management has led to better hazard identification, prevention strategies, and emergency response systems.

Statistics from the past decade indicate a steady decline in both minor and major incidents. For instance, the number of fatalities in mining operations has dropped to nearly negligible levels, reflecting a combination of technological innovation and rigorous safety practices.

### Future Challenges

Despite these advancements, the sector faces challenges such as maintaining low accident rates amidst expanding operations and ensuring equitable employment opportunities. Continued investment in worker training, safety infrastructure, and automation will be critical for sustaining progress in this area.

This section underscores Portugal's commitment to improving employment conditions and safety in mining, showcasing the sector as a model of transformation aligned with European standards.

## 4.4. Employment and Accident Rates in Mining in Andalucía, Castilla y León, and Extremadura

Over the past decades, the mining industry has seen substantial improvements in employment conditions, workplace safety, and a significant reduction in accident rates. These advancements have been achieved through stringent regulations, technological progress, and a strengthened focus on sustainability and workforce welfare.

In general, Spain has showed very significant reduction in mineral processing plants (PP), underground (UG) and open pit (OP) injuries throughout this period (see [13] for additional details).

### Current Employment Landscape

The mining sector in these regions provides stable employment, particularly in rural areas where economic alternatives may be limited. More than 12.500 direct employes were registered in 2022 in these regions.

Andalucía, with its rich deposits of copper, zinc, and other metals in the Iberian Pyrite Belt, has some of the most prominent operations in Spain, such as Cobre Las Cruces, Rio Tinto and Aguas Teñidas mines. These mines alone employ thousands of workers directly and indirectly, contributing significantly to the regional economy.

In Castilla y León, the mining of tungsten, and slate continues to be a major source of employment. Notable projects like the Barruecopardo Mine for tungsten and ongoing gold mining initiatives near León have generated opportunities for skilled and semi-skilled workers.

Similarly, Extremadura is experiencing a mining resurgence, driven by lithium exploration projects, which are expected to create hundreds of jobs in the coming years.

Efforts to promote diversity and gender inclusivity in the workforce are gaining momentum across these regions, supported by targeted training programs designed to prepare workers for modern, technology-driven mining operations.

## Improvement in Working Conditions

The modernization of mining operations over the last three decades has revolutionized working conditions in these regions. In the past, labor-intensive methods dominated, exposing workers to significant health and safety risks. However, the introduction of automation, mechanized processes, and stricter safety standards has transformed mining into a safer and more sustainable industry.

Some key improvements include:

- Safety Measures: Modern ventilation systems, protective equipment, and hazard detection technologies have become standard.
- Worker Training: Continuous education programs have equipped workers with the skills needed to operate advanced machinery and manage risks effectively.
- Health Standards: Regular medical check-ups and health monitoring programs have improved workers' overall well-being.

These advancements align with EU directives, ensuring that Spain's mining sector meets the highest safety and labor standards.

## Reduction in Accidents and Victims

Accident rates in the mining sector of these regions have seen a dramatic decline over the decades. Fatalities and severe injuries, once prevalent, have become rare occurrences due to several factors:

- Regulatory Oversight: Compliance with laws such as the Mining Safety Regulations and periodic inspections by authorities have strengthened workplace safety.
- Advanced Equipment: The use of automated machinery has minimized the need for direct human intervention in hazardous tasks, significantly reducing risks.
- Proactive Safety Culture: Mining companies have embraced a culture of prevention, prioritizing risk assessment and emergency preparedness.

For instance, in Andalucía, accidents per 1,000 workers have decreased by over 70% since the 1990s. Castilla y León and Extremadura have similarly benefited from improved risk management systems, achieving near-zero fatality rates in recent years (see [15, 16]).

## Future Challenges and Opportunities

Despite these achievements, challenges remain, including:

- Adapting to the rising demand for critical raw materials like lithium while maintaining high safety standards.
- Ensuring equitable employment opportunities and inclusivity across all demographics.
- Continuing to reduce the residual risks associated with legacy mining sites.

Looking forward, sustainable practices and investment in safety technologies will be crucial to maintaining progress. Public and private collaboration is expected to drive further innovation in workforce safety and environmental stewardship.

This section highlights how Andalucía, Castilla y León, and Extremadura have evolved into models of safe and sustainable mining practices. Through enhanced employment conditions and a steadfast focus on safety, these regions are contributing to a resilient and forward-looking mining sector.

# 5. Main minerals and mining waste

The work on the frame of the mining waste is the most developed one in this report. Here the complete procedure is briefly described and applied to the available data.

## 5.1. Data acquisition and management

This section describes the overall data availability, specific data contents and the preliminary handling of the different datasets.

### Available contents

A number of different datasets were finally available for the project and the specific fields retrieved are the following:

a. Portugal. Data provided by ACPMR (partners of I4-GREEN), produced by National Mining Authority through Direção Geral de Energia e Geologia (DGEG) and Empresa de Desenvolvimento Mineiro (EDM) [28] includes a KMZ with an associated shapefile. The attribute table (245 deposits) includes names, perimeter and area data of the sites, as well as a comments field. The KMZ gives the perimeters of the different sites, allowing to calculate the centroids of each one, with aims of mapping the overall sets of mine waste deposits. Three data files are provided with information about the inventoried sites. See the attached files: *DATA_Portugal_EDM.xlsx*, *DATA_Portugal_DGEG.xlsx*, and *DATA_Portugal_ENC.xlsx*

b. Andalucía. The data used belongs to the IMINA project, that was carried out from the regional government of Andalucía during recent years. This project involved a huge field and laboratory works in order to get an inventory of almost 4000 mine sites throughout the region. The data obtained required by the project included the following (among other contents not used in this project, as official registry entries, photographic and other contents):
   - Geographical coordinates.
   - Type of mine waste structures (ponds, dams, dumps or piles).
   - Type of mine waste material (waste solutions, tailings or fractured rocks).
   - Mine waste sampling.
   - Mine waste analytical tests (in-situ soil analysis, water and rocks laboratory analysis).

   Two data files are provided with information about the inventoried sites. See the attached files: *DATA_Andalucia_JDA.xlsx* and *DATA_Andalucia_INFOIGME.xlsx.*

c. Castilla y León. Here one finds two sources of data provided by ICAMCYL: First, a selection of the National Inventory of Waste Dumps, carried out by the Spanish Geological Survey (IGME) in 2002 [24], which contains the 465 sites inventoried in Castilla y León, corresponding to all types of mining (coal, metallics, aggregates, ornamental). Second, a selection of the BD from the Geological and Mining Map of Castilla y León, carried out by SIEMCALSA in 1997 [25], with 424 mines of metallic and industrial minerals, as well as uranium, which could present some interest in its mining residues as source of valuable raw materials. Unfortunately, both database cannot be correlated, so the first one could serve as an overview of the most important deposits regarding the volume of the residues, while the second could serve as a basis for future exploration of CRMs and other valuables materials contained in the mining wastes.

Two data files are provided with information about the inventoried sites. See the attached files: *DATA_CyL_MGMCYL.xlsx* and *DATA_CyL_INDL.xlsx*.

d. Extremadura. A database (excel file) with the information of the main tailing dams in Extremadura, coming from the National Inventory of tailing dams [29], can be found in the attached file: *DATA_Extremadura_INDL.xlsx*

Attached to this report, a database, composed by several .xlsx files, is provided gathering the related information.

The next figure shows the distribution of tailing dams (a) and mining waste deposits (b) in Spain. [22] Yellow marks; coal, Red marks Metallic minerals, Green marks; industrial minerals.

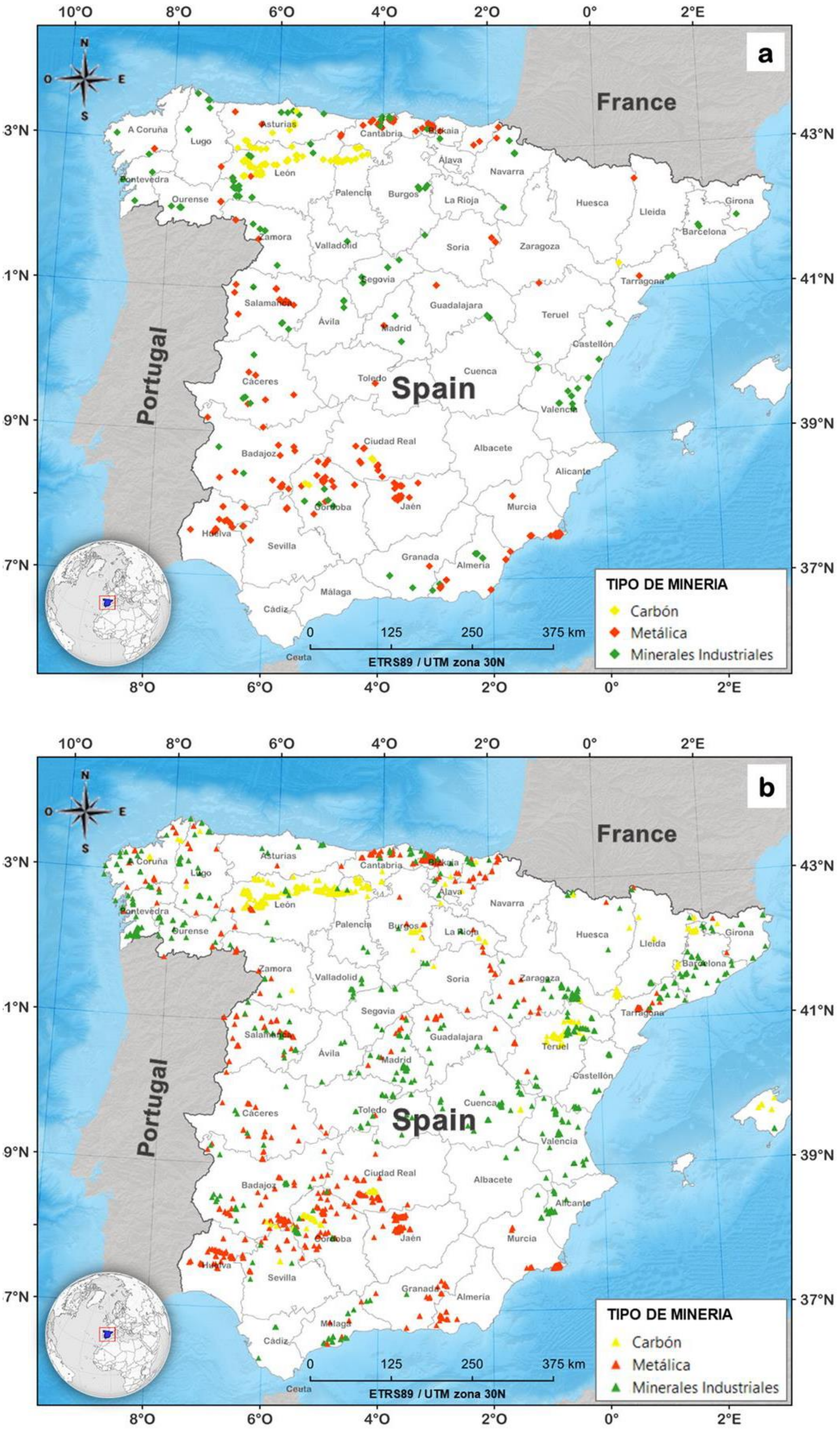


FIGURE 1: DISTRIBUTION OF TAILING DAMS (A) AND MINING WASTE DEPOSITS (B) IN SPAIN. [22]

## Screening and filtering

First, a preliminary overall inspection of the data was done, which allowed for the identification of some abnormal data and outliers, as well as no-data fields that were also screened in order to avoid further erroneous calculations (i.e. "-1" fields can contaminate the statistical calculations).

## Data Handling

Data availability was much higher and complete in Andalucía. The data available for Castilla y León, Extremadura and all the Portuguese regions at this moment, does not have chemical and mineralogical information enough to make a coherent analysis, so, this section will describe the data handling for Andalucía. In any case, if during the rest of this project the responsible regional or national bodies in charge of this information share with us this type of information, then an updated version of this report will be performed.

The IMINA dataset was stored in a spreadsheet book, with the different data distributed in a number of tabs. In order to get a single table with all the data relevant to I4-GREEN, a number of data operations was applied to the spreadsheet:

a. Copying location data such as the name, province and geographical coordinates.
b. Merging and copying waste structures data. The merging is necessary because each location can contain from zero to 1+ structures. The process keeps the difference between water-based structures (dams), tailing-based structures (ponds) and rock and soil-based structures (dumps and piles).
c. Merging and copying analytical data. According to the previously described criteria, the merging is necessary because each location can contain from zero data, up to a high number of samples (i.e. more than 50 for a single location). The process keeps the difference between soil in-situ laser analysis, water laboratory analysis and rock laboratory analysis (i.e., ICP-MS).

The final result is a single table with one registry for each location, which summarizes each location data. The data is then ready to be used in the further steps of the overall procedure.

## Data integration

Due to the lack of sufficient data homogeneity, the integration of the data correspondent to the target regions of the I4-GREEN Project, has been made in terms of putting together the overall datasheets in a single worksheet, but distributing the contents in different tabs.

## 5.2. Calculations

The calculations applied to the available data were conducted by using the following:

- Python language by using Jupyter Lab command interpreter and the following libraries: Pandas, Numpy, MatPlotLib (Pyplot), Sklearn (StandardScaler, Means, DBSCAN, PCA), Seaborn, Sqlite3, Geopandas, Folium (HeatMap).
- MS-Excel by using the in-built functions and VBA functionality.

## Linear Statistics

Linear statistics analyze relationships between variables assuming linear dependency, often using measures like the mean µ, sum S, median, mode, quartile computations. Having a population of N measures, the sum S and the mean can be written as:

$$S = \sum_{i=1}^{N} x_i$$

$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i$$

- Advantages
  - Simple to compute and interpret.
  - Well-suited for normally distributed data.
- Disadvantages
  - Limited to linear relationships.
  - Failing to capture complex, non-linear dependencies.

In this work these statistics have been used to characterize the datasets.

## 2nd Order Statistics

Second-order statistics involve measures that use pairwise relationships between variables, such as variance $\sigma^2$, covariance Cov(X,Y), correlation R(X,Y, k) and spectral density in the frequency domain. The first three figures stand with the following expressions:

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N} (x_i - \mu)^2$$

$$\mathrm{Cov}(X, Y) = \frac{1}{N}\sum_{i=1}^{N} (x_i - \mu_X)(y_i - \mu_Y)$$

$$R_{xy}(k) = \sum_{i=1}^{N-k} x_i y_{i+k}$$

- Advantages
  - Provide insights into the energy and correlation structure of signals.
  - Useful in many engineering applications like signal processing and system analysis.
- Disadvantages
  - Cannot fully capture higher-order relationships or non-Gaussian distributions.

In this work these statistics have been computed in order to gather and identify internal relations among variables (i.e. identify paragenesis with aims of further research).

TABLE 1. EXAMPLE OF 1ST ORDER STATISTICS FOR SELECTED ELEMENTS IN WATER SAMPLES

| Parameter | Maximum | Minimum | Mean | Median | Standard deviation | Variance | coefficient of variation |
|---|---|---|---|---|---|---|---|
| aluminum | 7.0E-01 | 1.2E-04 | 3.5E-01 | 3.5E-01 | 3.8E-01 | 1.1E-01 | 110.38 |
| arsenic | 1.3E-02 | 6.4E-05 | 6.4E-03 | 6.4E-03 | 8.9E-03 | 4.0E-05 | 140.01 |
| cadmium | 3.2E-04 | 1.3E-04 | 2.2E-04 | 2.2E-04 | 1.4E-04 | 9.3E-09 | 61.51 |
| cobalt | 5.5E-03 | 2.0E-04 | 2.9E-03 | 2.9E-03 | 3.7E-03 | 7.0E-06 | 131.32 |
| copper | 1.6E-01 | 1.5E-05 | 7.5E-02 | 7.1E-02 | 7.5E-02 | 4.2E-03 | 99.79 |
| chromium | 5.4E-04 | 5.4E-04 | 5.4E-04 | 5.4E-04 | 0.0E+00 | 0.0E+00 | 0.00 |
| mercury | 5.4E-04 | 1.2E-07 | 2.7E-04 | 2.7E-04 | 3.8E-04 | 7.2E-08 | 141.36 |
| molybdenum | 1.7E-01 | 5.4E-04 | 5.6E-02 | 2.2E-03 | 9.5E-02 | 6.0E-03 | 169.06 |
| nickel | 1.5E-01 | 7.8E-05 | 5.0E-02 | 4.9E-03 | 8.2E-02 | 4.5E-03 | 164.61 |
| lead | 1.5E+00 | 5.4E-04 | 7.7E-01 | 7.7E-01 | 1.1E+00 | 5.9E-01 | 141.32 |
| selenium | 8.8E-04 | 5.4E-04 | 7.1E-04 | 7.1E-04 | 2.5E-04 | 3.0E-08 | 34.71 |
| vanadium | 9.0E-04 | 5.4E-04 | 7.2E-04 | 7.2E-04 | 2.6E-04 | 3.3E-08 | 35.64 |
| zinc | 4.6E-01 | 5.6E-05 | 1.5E-01 | 7.4E-02 | 2.1E-01 | 3.3E-02 | 137.75 |

TABLE 2: EXAMPLE OF 1ST ORDER STATISTICS FOR SELECTED ELEMENTS IN SOLID SAMPLES (AT LABORATORY)

| Parameter | Maximum | Minimum | Mean | Median | Standard deviation | Variance | coefficient of variation |
|---|---|---|---|---|---|---|---|
| aluminum | 6.3E+06 | 5.6E-01 | 5.3E+04 | 7.9E+02 | 4.6E+05 | 2.1E+11 | 867.07 |
| arsenic | 4.2E+05 | 4.3E-04 | 2.9E+03 | 1.0E+01 | 3.1E+04 | 9.5E+08 | 1056.70 |
| cadmium | 5.5E+02 | 1.9E-05 | 9.5E+00 | 8.7E-02 | 5.1E+01 | 2.6E+03 | 536.25 |
| cobalt | 1.2E+04 | 9.8E-05 | 1.1E+02 | 1.1E+00 | 9.4E+02 | 8.7E+05 | 819.32 |
| copper | 1.6E+05 | 1.5E-03 | 1.6E+03 | 1.1E+01 | 1.2E+04 | 1.5E+08 | 768.87 |
| chromium | 8.3E+03 | 2.9E-04 | 9.2E+01 | 2.4E+00 | 6.3E+02 | 4.0E+05 | 688.02 |
| mercury | 2.1E+03 | 2.4E-06 | 2.0E+01 | 3.8E-02 | 1.6E+02 | 2.6E+04 | 824.48 |
| molybdenum | 3.7E+03 | 9.6E-05 | 4.2E+01 | 2.8E-01 | 3.0E+02 | 8.9E+04 | 722.15 |
| nickel | 5.0E+03 | 9.8E-05 | 7.6E+01 | 1.5E+00 | 4.3E+02 | 1.9E+05 | 570.60 |
| lead | 6.7E+05 | 9.1E-04 | 5.3E+03 | 5.5E+01 | 4.9E+04 | 2.4E+09 | 929.36 |
| selenium | 7.5E+03 | 2.2E-04 | 8.6E+01 | 2.2E-01 | 6.9E+02 | 4.8E+05 | 803.02 |
| vanadium | 7.7E+03 | 2.9E-04 | 9.1E+01 | 2.0E+00 | 6.1E+02 | 3.8E+05 | 678.58 |
| zinc | 1.4E+05 | 2.7E-03 | 1.4E+03 | 1.4E+01 | 1.1E+04 | 1.1E+08 | 768.18 |

TABLE 3: EXAMPLE OF 1ST ORDER STATISTICS FOR SELECTED ELEMENTS IN SOLID SAMPLES (XRP IN-SITU METHOD)

| Parameter | Maximum | Minimum | Mean | Median | Standard deviation | Variance | coefficient of variation |
|---|---|---|---|---|---|---|---|
| aluminium | 2.1E+07 | 1.9E+01 | 7.9E+05 | 5.7E+03 | 3.6E+06 | 1.2E+13 | 455.47 |
| antimony | 8.7E+01 | 1.0E-04 | 3.3E+00 | 2.1E-02 | 1.5E+01 | 2.1E+02 | 447.90 |
| arsenic | 7.5E+01 | 3.3E-06 | 2.4E+00 | 1.7E-03 | 1.3E+01 | 1.6E+02 | 536.84 |
| sulphur | 1.5E+07 | 1.8E-01 | 5.0E+05 | 1.1E+03 | 2.5E+06 | 6.1E+12 | 500.33 |
| bismuth | 1.8E+01 | 2.4E-05 | 7.0E-01 | 3.4E-03 | 3.1E+00 | 9.2E+00 | 438.50 |
| cadmium | 4.5E+01 | 5.8E-05 | 1.7E+00 | 9.6E-03 | 7.6E+00 | 5.7E+01 | 455.87 |
| calcium | 1.4E+06 | 5.9E-01 | 8.5E+04 | 1.0E+03 | 2.8E+05 | 7.5E+10 | 325.65 |
| cobalt | 2.6E+01 | 1.3E-05 | 9.2E-01 | 2.5E-03 | 4.3E+00 | 1.8E+01 | 469.17 |
| copper | 4.2E+01 | 1.3E-06 | 1.6E+00 | 3.4E-03 | 7.2E+00 | 5.0E+01 | 447.61 |
| chromium | 1.4E+05 | 8.8E-02 | 4.9E+03 | 1.3E+01 | 2.3E+04 | 5.2E+08 | 473.11 |
| tin | 5.3E+01 | 9.4E-05 | 2.1E+00 | 1.6E-02 | 9.2E+00 | 8.1E+01 | 427.60 |
| strontium | 5.0E+00 | 3.3E-06 | 2.1E-01 | 7.9E-04 | 9.0E-01 | 7.9E-01 | 421.12 |
| phosphorus | 3.3E+05 | 2.4E-01 | 1.3E+04 | 5.6E+01 | 5.7E+04 | 3.2E+09 | 440.26 |
| iron | 9.4E+07 | 1.4E+01 | 3.5E+06 | 6.0E+03 | 1.6E+07 | 2.5E+14 | 459.35 |
| yttrium | 3.1E+00 | 8.1E-07 | 1.1E-01 | 3.9E-04 | 5.2E-01 | 2.6E-01 | 490.51 |
| LE | 3.9E+04 | 4.2E-02 | 1.4E+03 | 5.8E+00 | 6.6E+03 | 4.3E+07 | 468.31 |
| magnesium | 1.9E+07 | 1.3E+01 | 7.0E+05 | 1.9E+03 | 3.3E+06 | 1.0E+13 | 472.05 |
| manganese | 4.5E+05 | 3.0E-01 | 1.9E+04 | 1.0E+02 | 7.9E+04 | 6.1E+09 | 405.98 |
| mercury | 7.3E+00 | 9.1E-06 | 2.7E-01 | 1.4E-03 | 1.2E+00 | 1.5E+00 | 456.89 |
| molybdenum | 2.2E+00 | 6.9E-07 | 1.2E-01 | 5.6E-04 | 4.6E-01 | 2.0E-01 | 375.44 |
| niobium | 2.9E+00 | 9.0E-07 | 1.1E-01 | 3.3E-04 | 4.9E-01 | 2.3E-01 | 443.51 |
| nickel | 6.6E+00 | 1.9E-06 | 2.2E-01 | 7.7E-04 | 1.1E+00 | 1.2E+00 | 508.47 |
| silver | 4.3E+01 | 4.7E-05 | 1.5E+00 | 7.8E-03 | 7.2E+00 | 5.1E+01 | 470.23 |
| lead | 2.1E+02 | 1.1E-06 | 7.3E+00 | 8.8E-03 | 3.6E+01 | 1.3E+03 | 492.08 |
| potassium | 7.1E+06 | 4.4E+00 | 2.7E+05 | 1.2E+03 | 1.2E+06 | 1.4E+12 | 452.30 |
| rubidium | 4.3E+00 | 2.3E-06 | 1.7E-01 | 9.6E-04 | 7.4E-01 | 5.4E-01 | 438.27 |
| selenium | 1.9E+00 | 1.3E-06 | 7.7E-02 | 2.6E-04 | 3.3E-01 | 1.1E-01 | 432.72 |
| silicon | 8.1E+07 | 1.2E+02 | 3.0E+06 | 1.9E+04 | 1.4E+07 | 1.8E+14 | 461.28 |
| titanium | 1.6E+06 | 1.6E+00 | 8.8E+04 | 3.5E+02 | 3.4E+05 | 1.1E+11 | 384.74 |
| thorium | 1.0E+01 | 1.2E-06 | 3.5E-01 | 1.2E-03 | 1.8E+00 | 3.0E+00 | 502.96 |
| uranium | 1.1E+01 | 1.6E-05 | 4.1E-01 | 2.4E-03 | 1.8E+00 | 3.3E+00 | 447.70 |
| vanadium | 7.3E+05 | 2.1E-01 | 3.9E+04 | 3.6E+01 | 1.6E+05 | 2.3E+10 | 397.32 |
| tungsten | 1.7E+01 | 1.3E-05 | 5.9E-01 | 2.5E-03 | 2.9E+00 | 8.1E+00 | 489.66 |
| zinc | 4.3E+01 | 5.6E-06 | 1.5E+00 | 4.0E-03 | 7.3E+00 | 5.2E+01 | 497.72 |
| zirconium | 8.0E+00 | 6.0E-06 | 3.0E-01 | 1.4E-03 | 1.4E+00 | 1.8E+00 | 448.57 |

## Higher-Order Statistics

Higher-order statistics extend beyond second-order, incorporating measures like skewness, kurtosis, and higher-order cumulants to capture more complex data characteristics.

$$\text{Skewness} = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^3}{\sigma^3}$$

$$\text{Kurtosis} = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^4}{\sigma^4} - 3$$

- Advantages
  - Capture non-linear dependencies and non-Gaussian features.
  - Useful in signal processing, outlier detection, and texture analysis.
- Disadvantages
  - Computationally intensive and harder to interpret.
  - Require larger datasets for reliable estimation.

In this case these data have not been applied in this stage of the work. The present datasets do not seem adequate for this purpose.

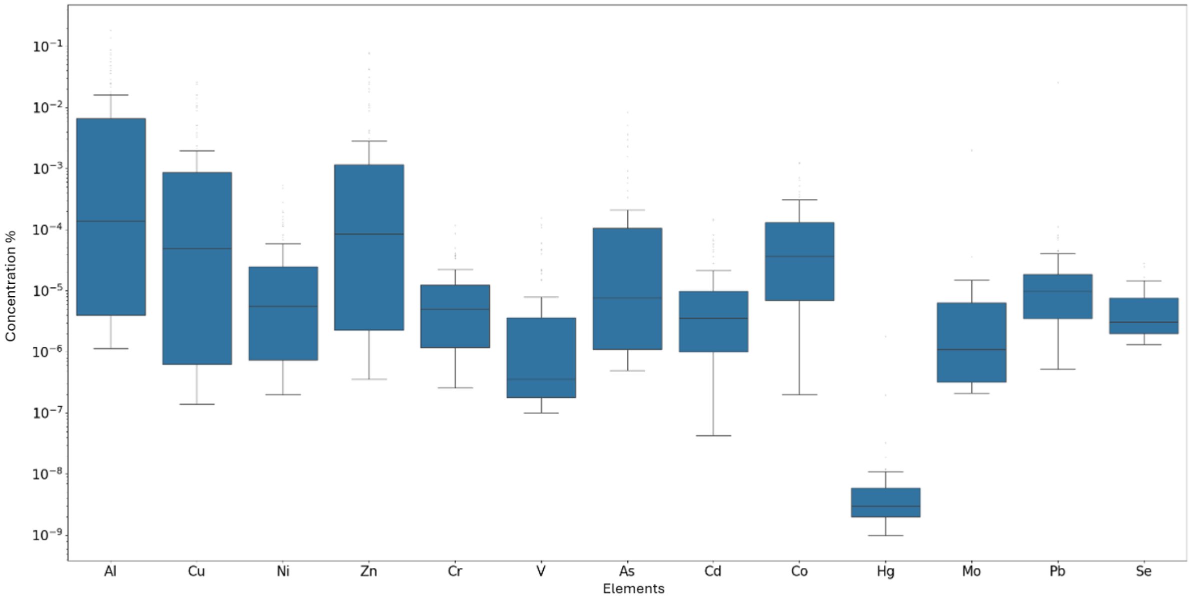


FIGURE 2. BOXPLOT OF THE WATER SAMPLES.

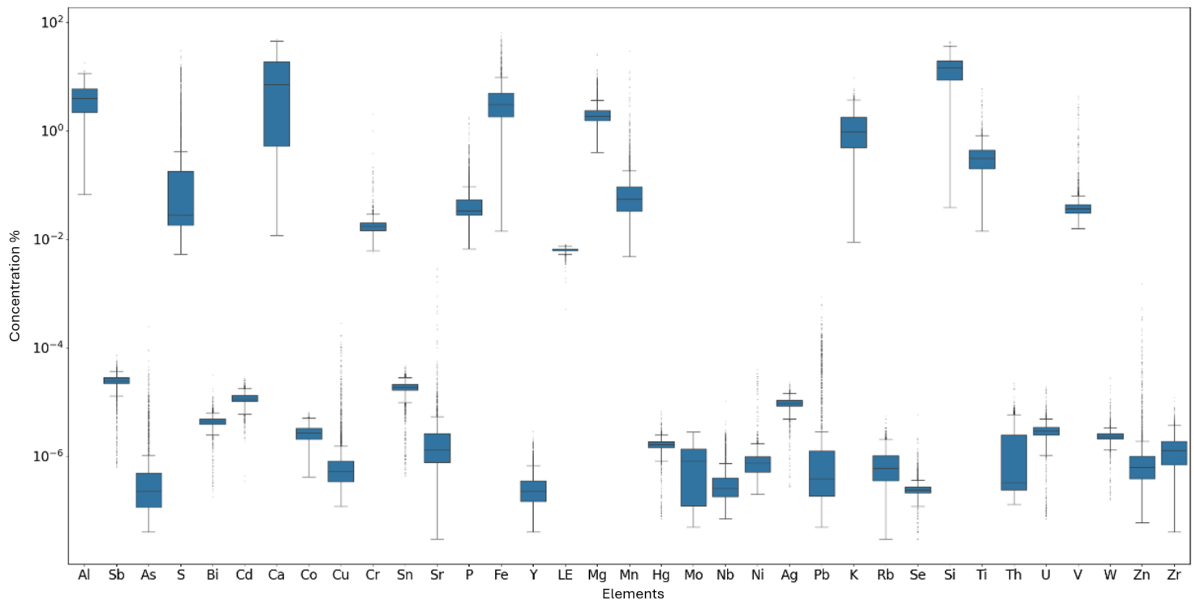


FIGURE 3. BOXPLOT OF THE IN-SITU SAMPLES.

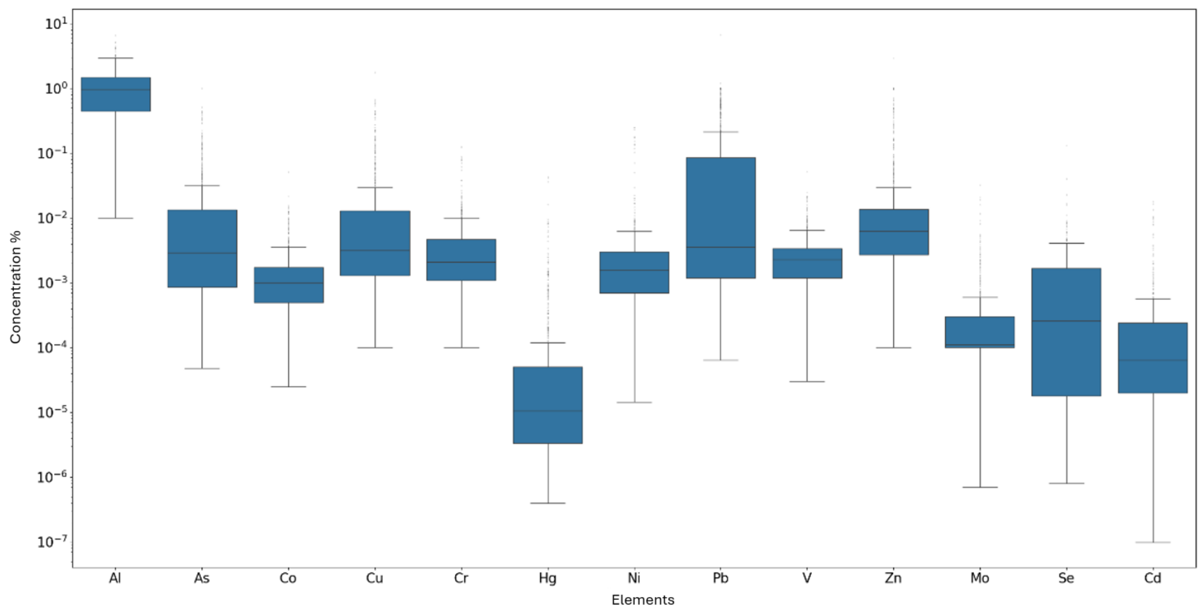


FIGURE 4. BOXPLOT OF THE LAB SAMPLES.

## Geographical Distribution

The next figures show geographical distribution of the mine sites (Andalucía) included in the available data pack. The four types of waste structures have been kept in order to better reflect the geographical distribution of such data.

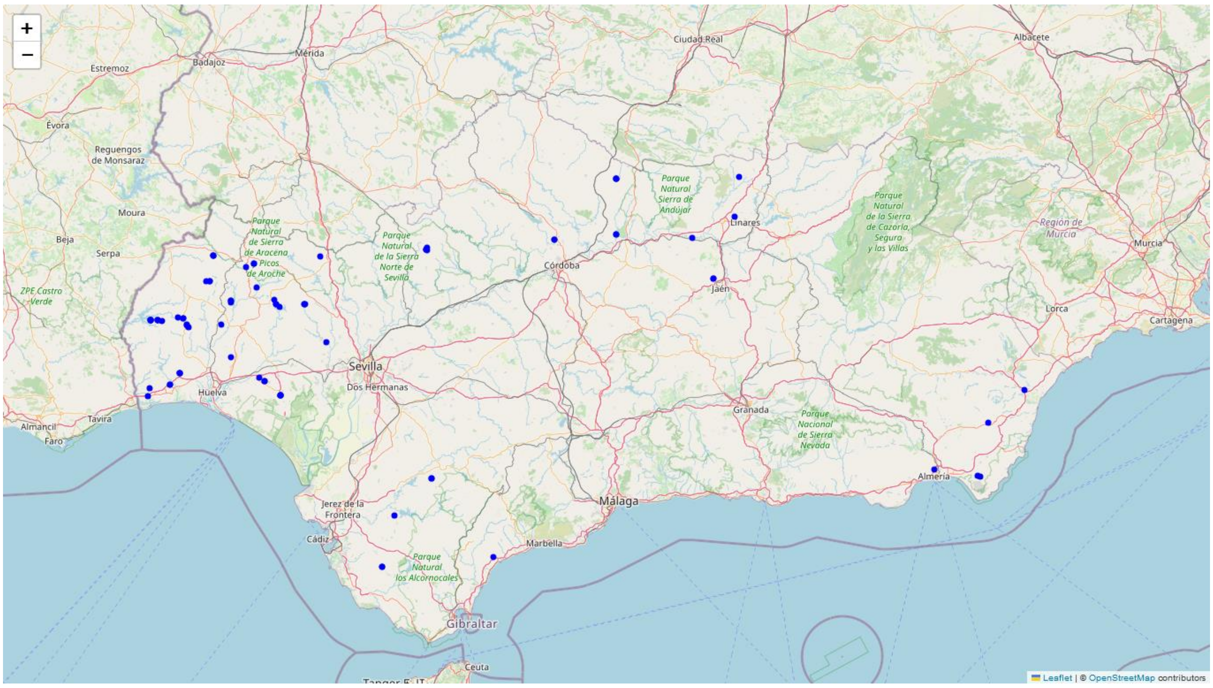


FIGURE 5. GEOGRAPHICAL DISTRIBUTION OF THE WASTE PONDS.

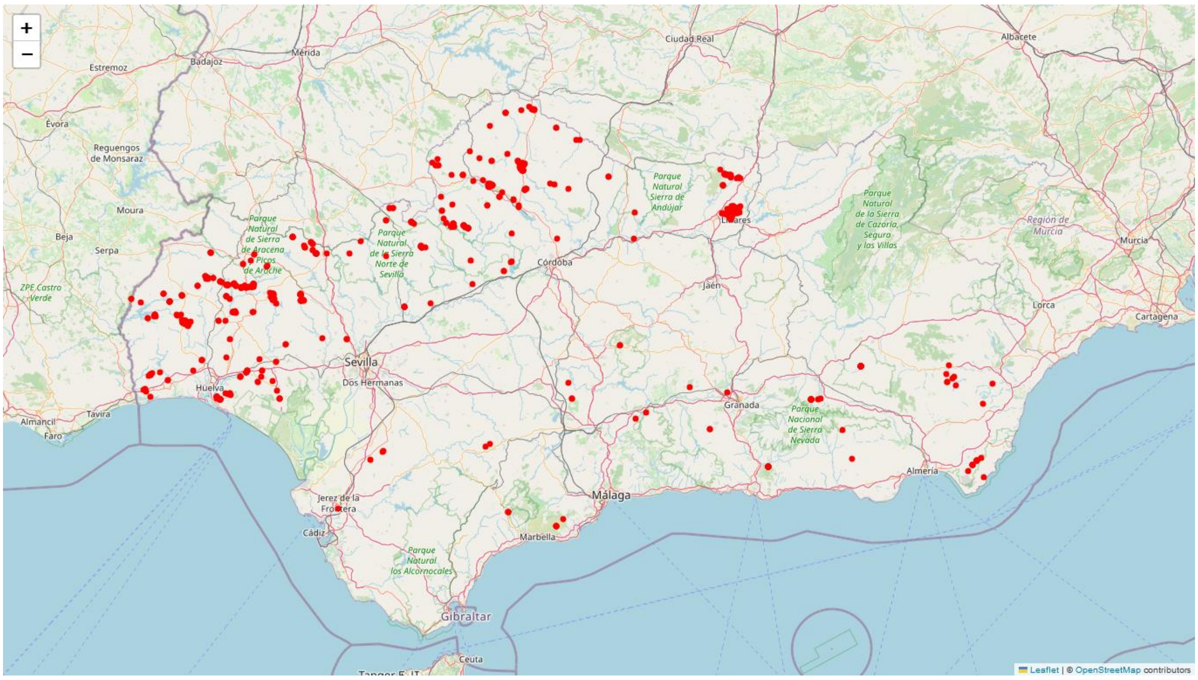


FIGURE 6. GEOGRAPHICAL DISTRIBUTION OF THE WASTE DUMPS.

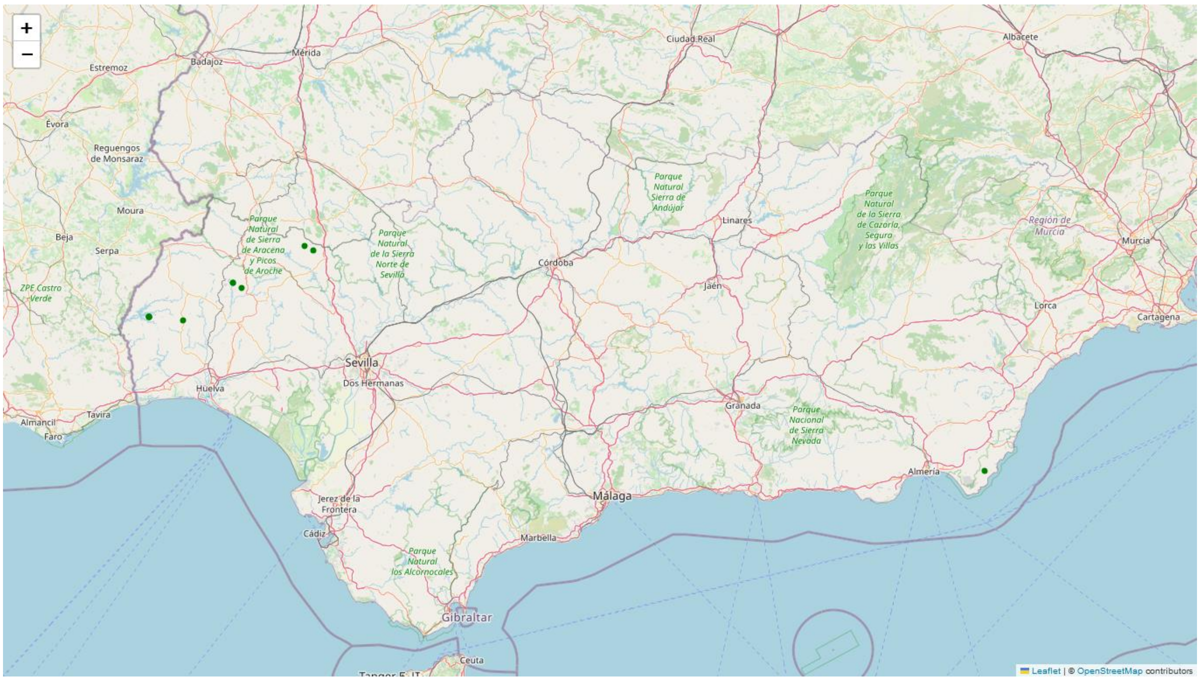


FIGURE 7. GEOGRAPHICAL DISTRIBUTION OF THE WASTE PILES.

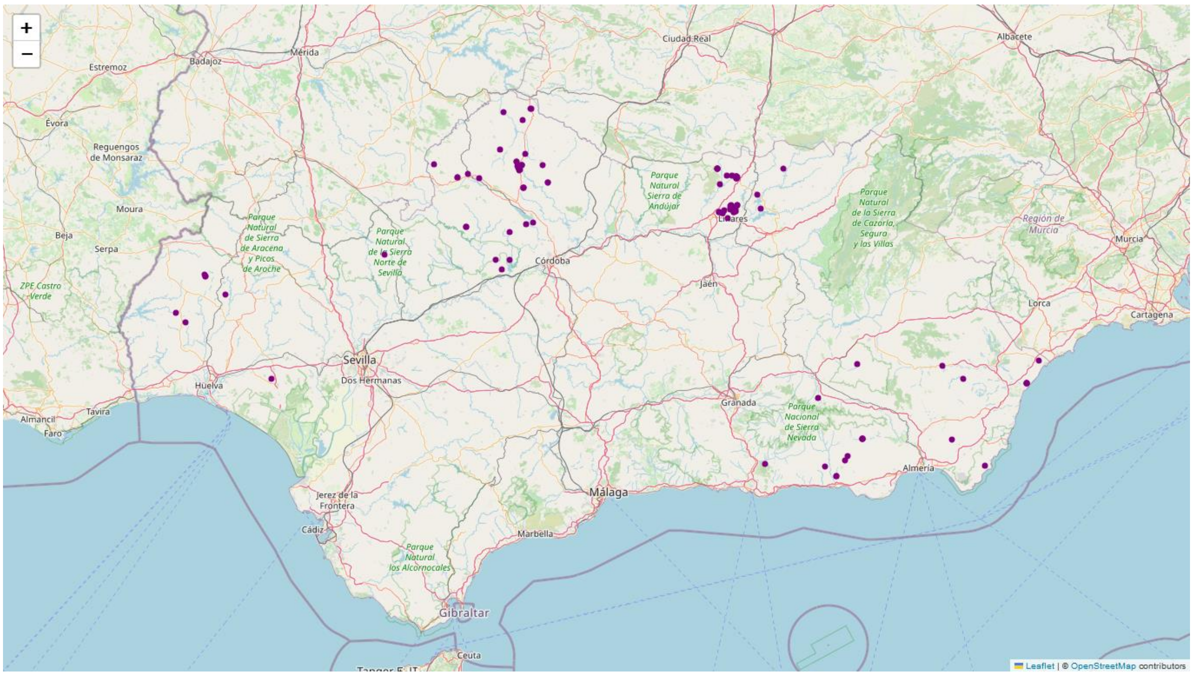


FIGURE 8. GEOGRAPHICAL DISTRIBUTION OF THE WASTE DAMS.

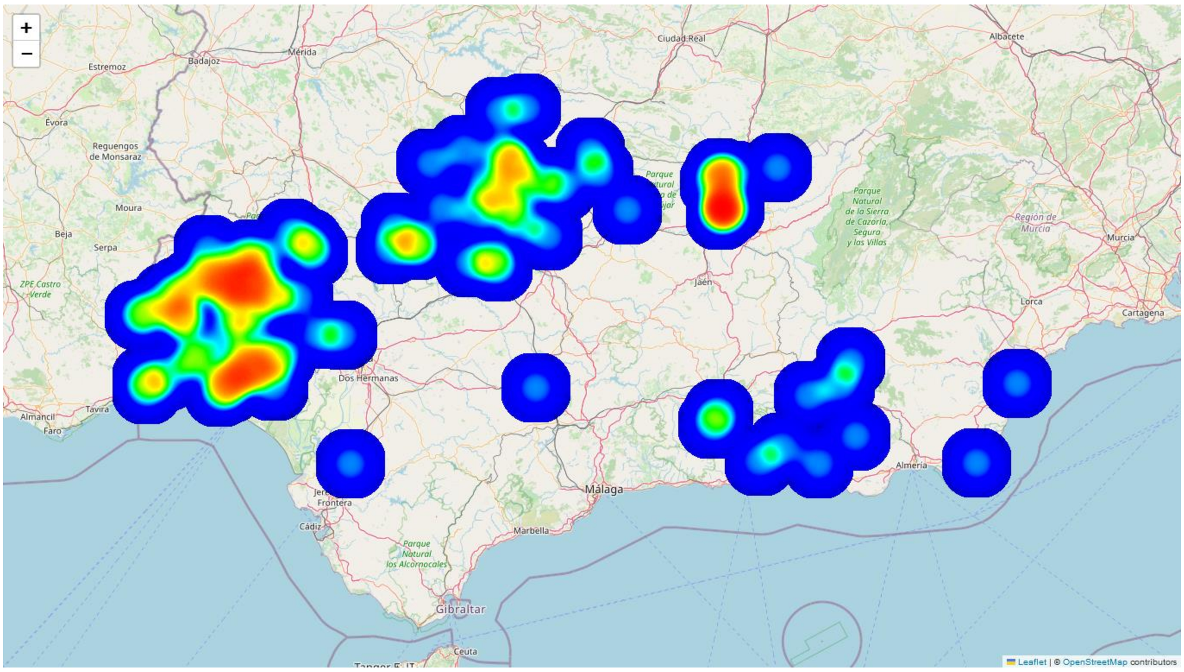


FIGURE 9. GEOGRAPHICAL CONCENTRATION OF MINE SITES IN THE REGION.

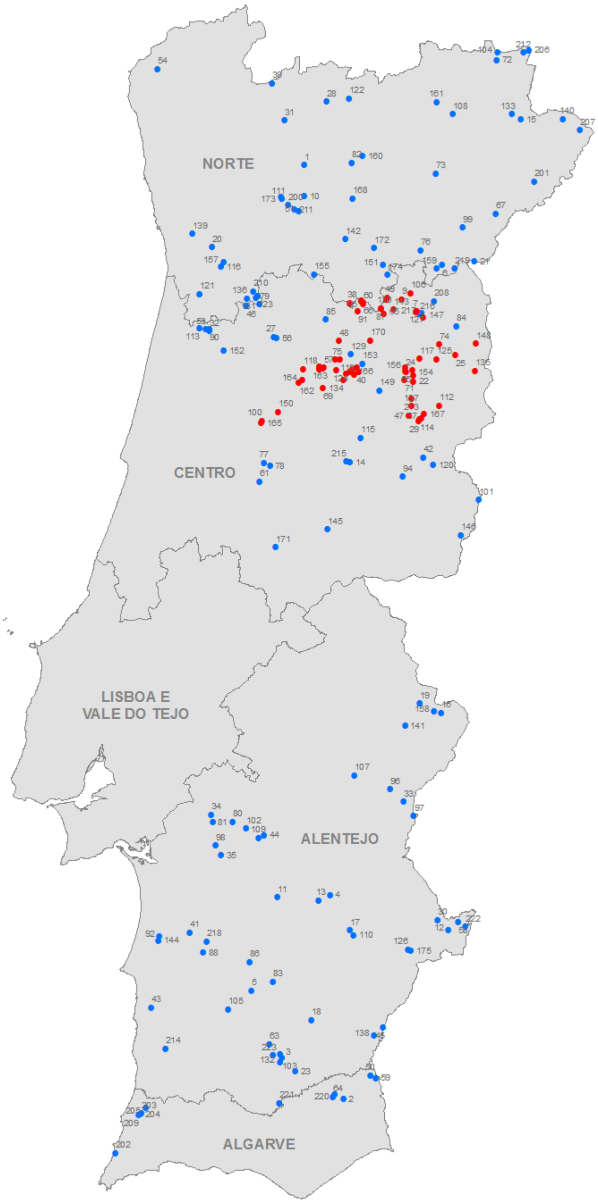


Figure 10 Geographical distribution of waste deposits in Portugal. EDM [30]

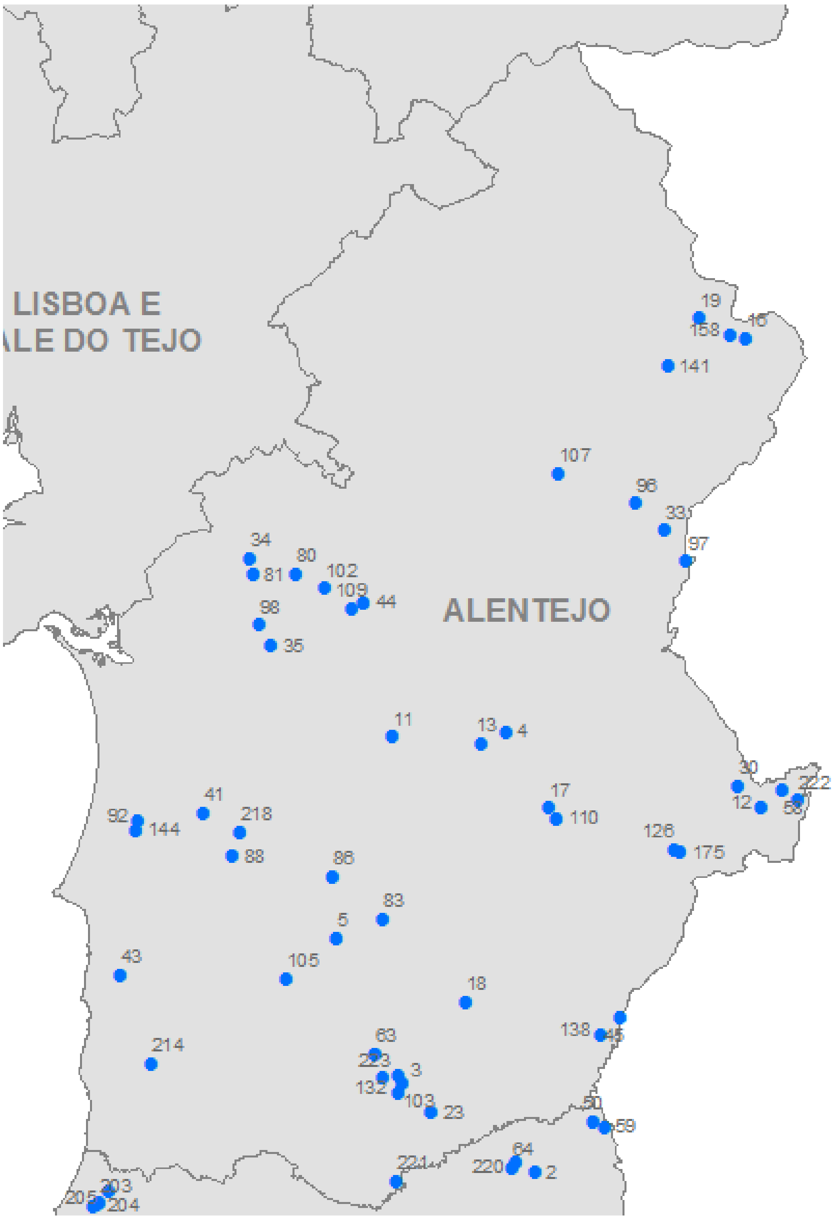


FIGURE 11 GEOGRAPHICAL DISTRIBUTION OF WASTE DEPOSITS IN ALENTEJO (PORTUGAL). EDM [30]

## Cross-Correlation

It is also interesting to gather some qualitative and quantitative feedback from the internal data structure. To face this, a cross-correlation matrix has been calculated for each type of waste structure.

Some interesting info was derived from this, especially in terms of setting some waste kind differences for each type of waste structure.

The following figures show the results obtained.

| | aluminium | antimony | arsenic | sulphur | bismuth | cadmium | calcium | cobalt | copper | chromium | tin | strontium |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| aluminium | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.87 | 1.00 | 1.00 | 1.00 | 1.00 | 0.52 |
| antimony | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.87 | 1.00 | 1.00 | 1.00 | 1.00 | 0.52 |
| arsenic | 0.99 | 0.99 | 1.00 | 1.00 | 0.98 | 0.99 | 0.83 | 0.99 | 0.99 | 0.99 | 0.98 | 0.40 |
| sulphur | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.84 | 1.00 | 1.00 | 1.00 | 0.99 | 0.48 |
| bismuth | 1.00 | 1.00 | 0.98 | 1.00 | 1.00 | 1.00 | 0.88 | 1.00 | 1.00 | 1.00 | 1.00 | 0.54 |
| cadmium | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.87 | 1.00 | 1.00 | 1.00 | 1.00 | 0.51 |
| calcium | 0.87 | 0.87 | 0.83 | 0.84 | 0.88 | 0.87 | 1.00 | 0.86 | 0.87 | 0.86 | 0.87 | 0.43 |
| cobalt | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 | 0.49 |
| copper | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.87 | 1.00 | 1.00 | 1.00 | 1.00 | 0.51 |
| chromium | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 | 0.49 |
| tin | 1.00 | 1.00 | 0.98 | 0.99 | 1.00 | 1.00 | 0.87 | 1.00 | 1.00 | 1.00 | 1.00 | 0.55 |
| strontium | 0.52 | 0.52 | 0.40 | 0.48 | 0.54 | 0.51 | 0.43 | 0.49 | 0.51 | 0.49 | 0.55 | 1.00 |
| phosphorus | 1.00 | 1.00 | 0.98 | 0.99 | 1.00 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 | 0.56 |
| iron | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.87 | 1.00 | 1.00 | 1.00 | 1.00 | 0.52 |
| yttrium | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.85 | 1.00 | 1.00 | 1.00 | 0.99 | 0.47 |
| LE | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 |
| magnesium | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.87 | 1.00 | 1.00 | 1.00 | 0.99 | 0.46 |
| manganese | 0.99 | 0.99 | 0.96 | 0.98 | 0.99 | 0.99 | 0.91 | 0.98 | 0.99 | 0.98 | 0.99 | 0.58 |
| mercury | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 | 0.52 |
| molybdenum | 0.88 | 0.88 | 0.80 | 0.85 | 0.89 | 0.87 | 0.75 | 0.86 | 0.87 | 0.85 | 0.89 | 0.87 |
| niobium | 0.99 | 1.00 | 0.99 | 0.99 | 1.00 | 1.00 | 0.85 | 1.00 | 1.00 | 1.00 | 1.00 | 0.52 |
| nickel | 0.99 | 0.99 | 1.00 | 1.00 | 0.99 | 1.00 | 0.85 | 1.00 | 1.00 | 1.00 | 0.99 | 0.44 |
| silver | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 | 0.49 |
| lead | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.83 | 1.00 | 1.00 | 1.00 | 0.99 | 0.49 |
| potassium | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.88 | 1.00 | 1.00 | 1.00 | 1.00 | 0.53 |
| rubidium | 1.00 | 1.00 | 0.98 | 0.99 | 1.00 | 1.00 | 0.88 | 0.99 | 1.00 | 1.00 | 1.00 | 0.56 |
| selenium | 0.99 | 0.99 | 0.97 | 0.98 | 0.99 | 0.99 | 0.84 | 0.98 | 0.99 | 0.98 | 0.99 | 0.63 |
| silicon | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.87 | 1.00 | 1.00 | 1.00 | 1.00 | 0.49 |
| titanium | 0.87 | 0.87 | 0.80 | 0.85 | 0.88 | 0.87 | 0.75 | 0.85 | 0.87 | 0.85 | 0.89 | 0.87 |
| thorium | 0.99 | 0.99 | 1.00 | 1.00 | 0.99 | 1.00 | 0.85 | 1.00 | 1.00 | 1.00 | 0.99 | 0.44 |
| uranium | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 | 0.54 |
| vanadium | 0.74 | 0.74 | 0.64 | 0.70 | 0.75 | 0.73 | 0.61 | 0.71 | 0.73 | 0.71 | 0.76 | 0.96 |
| tungsten | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.85 | 1.00 | 1.00 | 1.00 | 0.99 | 0.47 |
| zinc | 0.99 | 0.99 | 1.00 | 1.00 | 0.99 | 0.99 | 0.83 | 1.00 | 0.99 | 1.00 | 0.99 | 0.45 |
| zirconium | 1.00 | 1.00 | 0.98 | 1.00 | 1.00 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 | 0.55 |
| | | | | | | | | | | | | |
| Mean | 0.97 | 0.97 | 0.95 | 0.96 | 0.97 | 0.96 | 0.84 | 0.96 | 0.96 | 0.96 | 0.97 | 0.55 |

| | phosphorus | iron | yttrium | LE | magnesium | manganese | mercury | molybdenum | niobium | nickel | silver | lead |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| aluminium | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.88 | 0.99 | 0.99 | 1.00 | 1.00 |
| antimony | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.88 | 1.00 | 0.99 | 1.00 | 1.00 |
| arsenic | 0.98 | 0.99 | 1.00 | 0.99 | 0.99 | 0.96 | 0.99 | 0.80 | 0.99 | 1.00 | 0.99 | 1.00 |
| sulphur | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 | 0.85 | 0.99 | 1.00 | 1.00 | 1.00 |
| bismuth | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.89 | 1.00 | 0.99 | 1.00 | 0.99 |
| cadmium | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.87 | 1.00 | 1.00 | 1.00 | 1.00 |
| calcium | 0.86 | 0.87 | 0.85 | 0.86 | 0.87 | 0.91 | 0.86 | 0.75 | 0.85 | 0.85 | 0.86 | 0.83 |
| cobalt | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 |
| copper | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.87 | 1.00 | 1.00 | 1.00 | 1.00 |
| chromium | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 | 0.85 | 1.00 | 1.00 | 1.00 | 1.00 |
| tin | 1.00 | 1.00 | 0.99 | 1.00 | 0.99 | 0.99 | 1.00 | 0.89 | 1.00 | 0.99 | 1.00 | 0.99 |
| strontium | 0.56 | 0.52 | 0.47 | 0.50 | 0.46 | 0.58 | 0.52 | 0.87 | 0.52 | 0.44 | 0.49 | 0.49 |
| phosphorus | 1.00 | 1.00 | 0.99 | 1.00 | 0.99 | 0.99 | 1.00 | 0.90 | 1.00 | 0.99 | 1.00 | 1.00 |
| iron | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.87 | 1.00 | 1.00 | 1.00 | 1.00 |
| yttrium | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 | 0.84 | 1.00 | 1.00 | 1.00 | 1.00 |
| LE | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 |
| magnesium | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 | 0.84 | 0.99 | 1.00 | 1.00 | 1.00 |
| manganese | 0.99 | 0.99 | 0.98 | 0.98 | 0.98 | 1.00 | 0.99 | 0.90 | 0.98 | 0.97 | 0.98 | 0.98 |
| mercury | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.88 | 1.00 | 1.00 | 1.00 | 1.00 |
| molybdenum | 0.90 | 0.87 | 0.84 | 0.86 | 0.84 | 0.90 | 0.88 | 1.00 | 0.87 | 0.83 | 0.86 | 0.86 |
| niobium | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.98 | 1.00 | 0.87 | 1.00 | 0.99 | 1.00 | 1.00 |
| nickel | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 | 1.00 | 0.83 | 0.99 | 1.00 | 1.00 | 1.00 |
| silver | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 |
| lead | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 |
| potassium | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.88 | 0.99 | 0.99 | 1.00 | 0.99 |
| rubidium | 1.00 | 1.00 | 0.99 | 1.00 | 0.99 | 1.00 | 1.00 | 0.90 | 0.99 | 0.99 | 1.00 | 0.99 |
| selenium | 1.00 | 0.99 | 0.98 | 0.99 | 0.98 | 0.99 | 0.99 | 0.93 | 0.99 | 0.98 | 0.99 | 0.99 |
| silicon | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.86 | 1.00 | 1.00 | 1.00 | 1.00 |
| titanium | 0.89 | 0.87 | 0.84 | 0.86 | 0.84 | 0.90 | 0.87 | 1.00 | 0.87 | 0.82 | 0.85 | 0.85 |
| thorium | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 | 0.99 | 0.82 | 0.99 | 1.00 | 1.00 | 1.00 |
| uranium | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.89 | 1.00 | 0.99 | 1.00 | 1.00 |
| vanadium | 0.77 | 0.73 | 0.70 | 0.72 | 0.69 | 0.78 | 0.74 | 0.97 | 0.73 | 0.67 | 0.71 | 0.71 |
| tungsten | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 | 0.84 | 0.99 | 1.00 | 1.00 | 1.00 |
| zinc | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 0.97 | 0.99 | 0.83 | 0.99 | 1.00 | 1.00 | 1.00 |
| zirconium | 1.00 | 1.00 | 0.99 | 1.00 | 0.99 | 0.99 | 1.00 | 0.89 | 1.00 | 0.99 | 1.00 | 1.00 |
| | | | | | | | | | | | | |
| Mean | 0.97 | 0.97 | 0.96 | 0.96 | 0.96 | 0.96 | 0.97 | 0.87 | 0.96 | 0.96 | 0.96 | 0.96 |

| | potassium | rubidium | selenium | silicon | titanium | thorium | uranium | vanadium | tungsten | zinc | zirconium |
|---|---|---|---|---|---|---|---|---|---|---|---|
| aluminium | 1.00 | 1.00 | 0.99 | 1.00 | 0.87 | 0.99 | 1.00 | 0.74 | 1.00 | 0.99 | 1.00 |
| antimony | 1.00 | 1.00 | 0.99 | 1.00 | 0.87 | 0.99 | 1.00 | 0.74 | 1.00 | 0.99 | 1.00 |
| arsenic | 0.99 | 0.98 | 0.97 | 0.99 | 0.80 | 1.00 | 0.99 | 0.64 | 1.00 | 1.00 | 0.98 |
| sulphur | 1.00 | 0.99 | 0.98 | 1.00 | 0.85 | 1.00 | 1.00 | 0.70 | 1.00 | 1.00 | 1.00 |
| bismuth | 1.00 | 1.00 | 0.99 | 1.00 | 0.88 | 0.99 | 1.00 | 0.75 | 1.00 | 0.99 | 1.00 |
| cadmium | 1.00 | 1.00 | 0.99 | 1.00 | 0.87 | 1.00 | 1.00 | 0.73 | 1.00 | 0.99 | 1.00 |
| calcium | 0.88 | 0.88 | 0.84 | 0.87 | 0.75 | 0.85 | 0.86 | 0.61 | 0.85 | 0.83 | 0.86 |
| cobalt | 1.00 | 0.99 | 0.98 | 1.00 | 0.85 | 1.00 | 1.00 | 0.71 | 1.00 | 1.00 | 1.00 |
| copper | 1.00 | 1.00 | 0.99 | 1.00 | 0.87 | 1.00 | 1.00 | 0.73 | 1.00 | 0.99 | 1.00 |
| chromium | 1.00 | 1.00 | 0.98 | 1.00 | 0.85 | 1.00 | 1.00 | 0.71 | 1.00 | 1.00 | 1.00 |
| tin | 1.00 | 1.00 | 0.99 | 1.00 | 0.89 | 0.99 | 1.00 | 0.76 | 0.99 | 0.99 | 1.00 |
| strontium | 0.53 | 0.56 | 0.63 | 0.49 | 0.87 | 0.44 | 0.54 | 0.96 | 0.47 | 0.45 | 0.55 |
| phosphorus | 1.00 | 1.00 | 1.00 | 1.00 | 0.89 | 0.99 | 1.00 | 0.77 | 0.99 | 0.99 | 1.00 |
| iron | 1.00 | 1.00 | 0.99 | 1.00 | 0.87 | 1.00 | 1.00 | 0.73 | 1.00 | 0.99 | 1.00 |
| yttrium | 1.00 | 0.99 | 0.98 | 1.00 | 0.84 | 1.00 | 1.00 | 0.70 | 1.00 | 1.00 | 0.99 |
| LE | 1.00 | 1.00 | 0.99 | 1.00 | 0.86 | 1.00 | 1.00 | 0.72 | 1.00 | 1.00 | 1.00 |
| magnesium | 1.00 | 0.99 | 0.98 | 1.00 | 0.84 | 1.00 | 1.00 | 0.69 | 1.00 | 1.00 | 0.99 |
| manganese | 0.99 | 1.00 | 0.99 | 0.99 | 0.90 | 0.97 | 0.99 | 0.78 | 0.98 | 0.97 | 0.99 |
| mercury | 1.00 | 1.00 | 0.99 | 1.00 | 0.87 | 0.99 | 1.00 | 0.74 | 1.00 | 0.99 | 1.00 |
| molybdenum | 0.88 | 0.90 | 0.93 | 0.86 | 1.00 | 0.82 | 0.89 | 0.97 | 0.84 | 0.83 | 0.89 |
| niobium | 0.99 | 0.99 | 0.99 | 1.00 | 0.87 | 0.99 | 1.00 | 0.73 | 0.99 | 0.99 | 1.00 |
| nickel | 0.99 | 0.99 | 0.98 | 1.00 | 0.82 | 1.00 | 0.99 | 0.67 | 1.00 | 1.00 | 0.99 |
| silver | 1.00 | 1.00 | 0.99 | 1.00 | 0.85 | 1.00 | 1.00 | 0.71 | 1.00 | 1.00 | 1.00 |
| lead | 0.99 | 0.99 | 0.99 | 1.00 | 0.85 | 1.00 | 1.00 | 0.71 | 1.00 | 1.00 | 1.00 |
| potassium | 1.00 | 1.00 | 0.99 | 1.00 | 0.88 | 0.99 | 1.00 | 0.74 | 1.00 | 0.99 | 1.00 |
| rubidium | 1.00 | 1.00 | 0.99 | 1.00 | 0.89 | 0.99 | 1.00 | 0.76 | 0.99 | 0.99 | 1.00 |
| selenium | 0.99 | 0.99 | 1.00 | 0.98 | 0.93 | 0.97 | 0.99 | 0.82 | 0.98 | 0.98 | 0.99 |
| silicon | 1.00 | 1.00 | 0.98 | 1.00 | 0.85 | 1.00 | 1.00 | 0.71 | 1.00 | 1.00 | 1.00 |
| titanium | 0.88 | 0.89 | 0.93 | 0.85 | 1.00 | 0.82 | 0.88 | 0.97 | 0.84 | 0.83 | 0.89 |
| thorium | 0.99 | 0.99 | 0.97 | 1.00 | 0.82 | 1.00 | 0.99 | 0.67 | 1.00 | 1.00 | 0.99 |
| uranium | 1.00 | 1.00 | 0.99 | 1.00 | 0.88 | 0.99 | 1.00 | 0.75 | 1.00 | 0.99 | 1.00 |
| vanadium | 0.74 | 0.76 | 0.82 | 0.71 | 0.97 | 0.67 | 0.75 | 1.00 | 0.69 | 0.68 | 0.76 |
| tungsten | 1.00 | 0.99 | 0.98 | 1.00 | 0.84 | 1.00 | 1.00 | 0.69 | 1.00 | 1.00 | 0.99 |
| zinc | 0.99 | 0.99 | 0.98 | 1.00 | 0.83 | 1.00 | 0.99 | 0.68 | 1.00 | 1.00 | 0.99 |
| zirconium | 1.00 | 1.00 | 0.99 | 1.00 | 0.89 | 0.99 | 1.00 | 0.76 | 0.99 | 0.99 | 1.00 |
| | | | | | | | | | | | |
| Mean | 0.97 | 0.97 | 0.96 | 0.96 | 0.87 | 0.96 | 0.97 | 0.75 | 0.96 | 0.95 | 0.97 |

FIGURE 1012. CROSS-CORRELATION RESULTS FOR PONDS WITH COLOR-FORMAT (DARK RED=NO CORR, DARK GREEN=FILL CORR)

| | aluminum | arsenic | cadmium | cobalt | copper | chromium | mercury | molybdenum | nickel | lead | selenium | vanadium | zinc |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| aluminum | 1.00 | 0.98 | 0.97 | 0.98 | 0.94 | 0.99 | 0.95 | 0.97 | 0.69 | 0.97 | 0.97 | 0.98 | 0.97 |
| arsenic | 0.98 | 1.00 | 0.94 | 0.96 | 0.94 | 0.96 | 0.98 | 0.94 | 0.53 | 1.00 | 1.00 | 0.92 | 0.97 |
| cadmium | 0.97 | 0.94 | 1.00 | 0.97 | 0.94 | 0.98 | 0.92 | 0.95 | 0.73 | 0.93 | 0.93 | 0.98 | 0.95 |
| cobalt | 0.98 | 0.96 | 0.97 | 1.00 | 0.98 | 0.99 | 0.94 | 0.96 | 0.64 | 0.95 | 0.96 | 0.96 | 0.97 |
| copper | 0.94 | 0.94 | 0.94 | 0.98 | 1.00 | 0.97 | 0.92 | 0.89 | 0.57 | 0.94 | 0.94 | 0.92 | 0.97 |
| chromium | 0.99 | 0.96 | 0.98 | 0.99 | 0.97 | 1.00 | 0.94 | 0.94 | 0.70 | 0.95 | 0.95 | 0.98 | 0.97 |
| mercury | 0.95 | 0.98 | 0.92 | 0.94 | 0.92 | 0.94 | 1.00 | 0.93 | 0.51 | 0.98 | 0.98 | 0.89 | 0.96 |
| molybdenum | 0.97 | 0.94 | 0.95 | 0.96 | 0.89 | 0.94 | 0.93 | 1.00 | 0.68 | 0.93 | 0.94 | 0.95 | 0.93 |
| nickel | 0.69 | 0.53 | 0.73 | 0.64 | 0.57 | 0.70 | 0.51 | 0.68 | 1.00 | 0.51 | 0.52 | 0.82 | 0.58 |
| lead | 0.97 | 1.00 | 0.93 | 0.95 | 0.94 | 0.95 | 0.98 | 0.93 | 0.51 | 1.00 | 1.00 | 0.91 | 0.98 |
| selenium | 0.97 | 1.00 | 0.93 | 0.96 | 0.94 | 0.95 | 0.98 | 0.94 | 0.52 | 1.00 | 1.00 | 0.91 | 0.98 |
| vanadium | 0.98 | 0.92 | 0.98 | 0.96 | 0.92 | 0.98 | 0.89 | 0.95 | 0.82 | 0.91 | 0.91 | 1.00 | 0.93 |
| zinc | 0.97 | 0.97 | 0.95 | 0.97 | 0.97 | 0.97 | 0.96 | 0.93 | 0.58 | 0.98 | 0.98 | 0.93 | 1.00 |
| | | | | | | | | | | | | | |
| Mean | 0.95 | 0.93 | 0.94 | 0.94 | 0.92 | 0.95 | 0.91 | 0.92 | 0.65 | 0.93 | 0.93 | 0.93 | 0.93 |

FIGURE 1113. CROSS-CORRELATION RESULTS FOR DUMPS WITH COLOR-FORMAT (DARK RED=NO CORR, DARK GREEN=FILL CORR).

## Clustering

In order to provide some kind of sorting of the available data, a clustering strategy was implemented [5, 6]. Any cluster procedure requires a n-dimensional field for distance measurement (not necessarily geographical or physically-based) and a number of data attributes to perform the distance analysis and optimization. Since the points have attributes in addition to their coordinates, it's advisable to use a clustering algorithm that works with spatial data and simultaneously considers the attributes. Here are some key methods:

A. Hierarchical Clustering

- Creates a hierarchy of clusters from all points separated to a single cluster.
- Can stop at the desired level of granularity.
- Similarity metrics:
    - Spatial distances: Euclidean, Manhattan.
    - Attribute similarity: Correlation, Cosine, etc.

B. DBSCAN or HDBSCAN

- Density-based clustering, ideal for irregular distributions.
- Identifies clusters by density and considers isolated points as "noise."
- Configurable with:
    - ε: Maximum distance between points in a cluster.
    - MinPts: Minimum number of points in a cluster.
- Extendable to multivariate data by combining attributes with coordinates.

C. k-means (with attribute extensions)

- Divides data into kk clusters with convex shapes.
- To combine coordinates and attributes:
    - Use a weighted distance metric (spatial + attributes).
    - Normalize variables before calculating distances.

D. Gaussian Mixture Models (GMM)

- Assumes data comes from a mixture of Gaussian distributions.
- Suitable for clusters with elliptical shapes.

The following items describe the overall process.

Problem Definition and Specific Objectives

The initial approach to solve this problem relies in the following:

1. Input
    - Spatial coordinates of the points: (x,y,z,… ).
    - A set of attributes associated with each point.
2. Output
    - Subsets or clusters of points.
3. Optimization Criterion
    - For example:
        - Minimize intra-cluster distances.
        - Maximize cohesion in the attributes of points within a cluster.
        - A weighted combination of both factors.
    - In this case, a weighted combination of both factors was applied.

Defining a Specific Algorithm

1. Preprocessing
    - Scale the coordinates and attributes (e.g., using Min-Max or Z-score).
    - Select the most relevant attributes.
2. Define Distance Metric
    - Spatial: $d_{spatial}$.
    - Attributes: $d_{attr}$.
    - Combine: $d=\alpha \cdot d_{spatial}+(1-\alpha)\cdot d_{attr}$, where α balances their relative importance.
3. Select and Apply the Algorithm
    - DBSCAN or HDBSCAN is suitable if you expect clusters of variable density.
    - k-means or GMM if the clusters have well-defined shapes.
4. Validate Results
    - Metrics: Silhouette, Davies-Bouldin, Inertia.

Alternatives

- In order to optimize a specific parameter, other methods like genetic algorithms or Bayesian search to find the best values for α, ε, etc.
- It is also possible to dynamically adjust the number of clusters using internal validation metrics (Silhouette, etc.).

## Clustering by Attributes and bi-plots

Clustering applied directly to attributes, without considering geographical coordinates, provides a focused way to group data based solely on shared characteristics. This approach is especially useful when attributes carry significant domain-specific meaning, such as chemical compositions, customer preferences, or sensor readings. By clustering based on attributes, patterns and relationships emerge that might otherwise be obscured by spatial considerations.

For example, in customer segmentation, clustering attributes like purchase history, age, or income can reveal distinct market groups, enabling tailored marketing strategies. Similarly, in industrial processes, clustering material properties such as density, hardness, or thermal conductivity helps identify subsets of materials with similar functional capabilities.

This method also supports dimensionality reduction and visualization. By grouping data with similar attributes, it becomes easier to summarize trends or outliers, making complex datasets more interpretable.

A key benefit is its flexibility in defining similarity. Distance metrics like Euclidean, Manhattan, or even more sophisticated methods like Mahalanobis can be used to capture the relationships most relevant to the data's context. Additionally, clustering algorithms such as k-means, DBSCAN, or Gaussian Mixture Models can be applied to discover natural groupings.

Ultimately, attribute-based clustering provides a powerful tool for extracting actionable insights, streamlining decision-making, and enhancing predictive modeling across diverse fields.

### Clustering by Geographical Coordinates

Clustering using geographical coordinates focuses on grouping data points based on their spatial proximity. This approach is particularly valuable in applications where location plays a critical role, such as urban planning, logistics, environmental monitoring, and retail site selection.

By measuring distances between points using geographical coordinates, clustering methods identify regions of high density, natural groupings, or isolated outliers. For instance, in urban development, clustering can highlight areas with concentrated infrastructure needs, such as transportation hubs or underserved neighborhoods. In environmental studies, it can pinpoint hotspots of pollution or biodiversity.

Spatial clustering benefits from well-defined distance metrics, such as Euclidean, Manhattan, or haversine (for latitude/longitude data on Earth's surface). Algorithms like DBSCAN or HDBSCAN are highly effective, as they detect clusters of variable density while distinguishing noise points, such as sparsely located outliers. Alternatively, k-means or hierarchical clustering can also be employed, particularly for evenly distributed data.

This method provides actionable insights for resource allocation and decision-making. For example, logistics companies can optimize delivery routes by clustering delivery points, while retail businesses can identify ideal locations for new stores based on customer distribution.

Geographical clustering empowers organizations to maximize spatial efficiency, enabling informed planning and enhanced operational effectiveness across diverse industries.

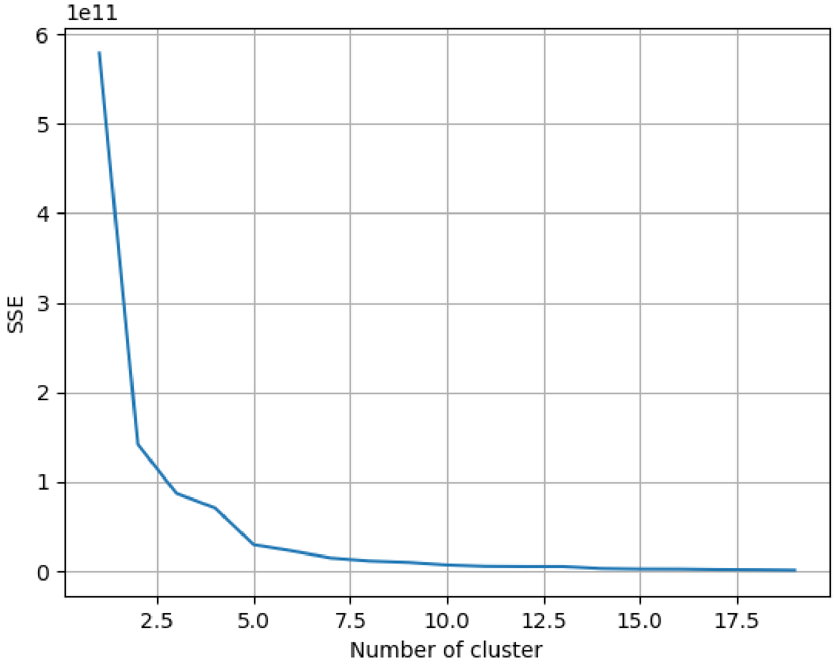


Figure 14. Determination of the optimal number of clusters for the waste ponds, by using the elbow method.

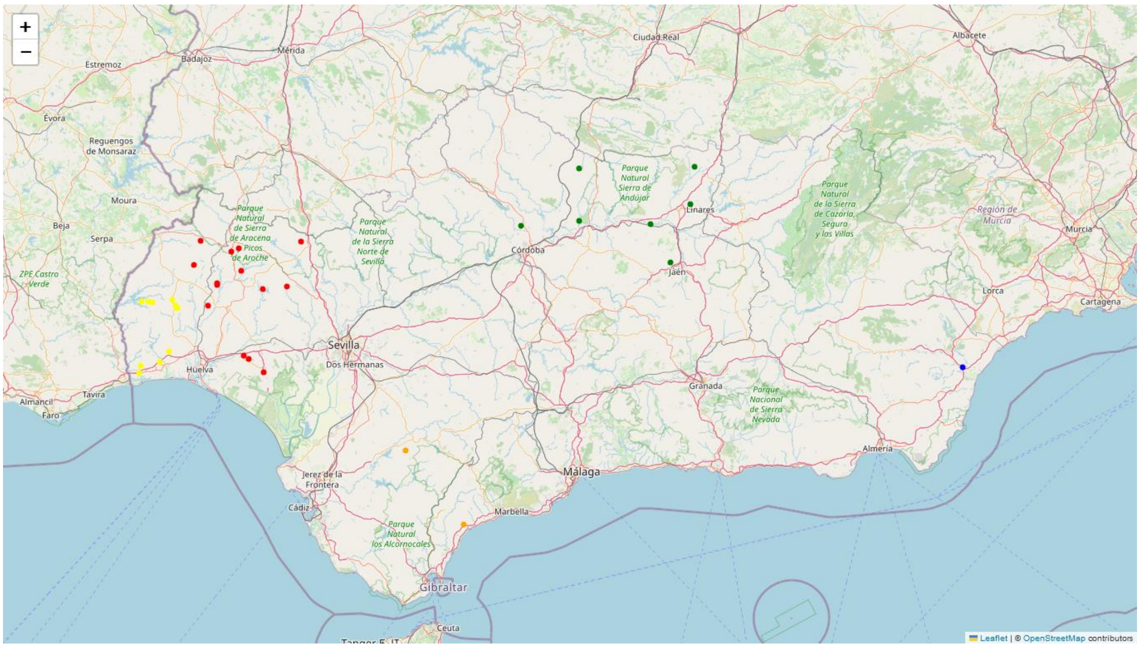


Figure 1125. Geo-cluster of the available ponds in the mine sites.

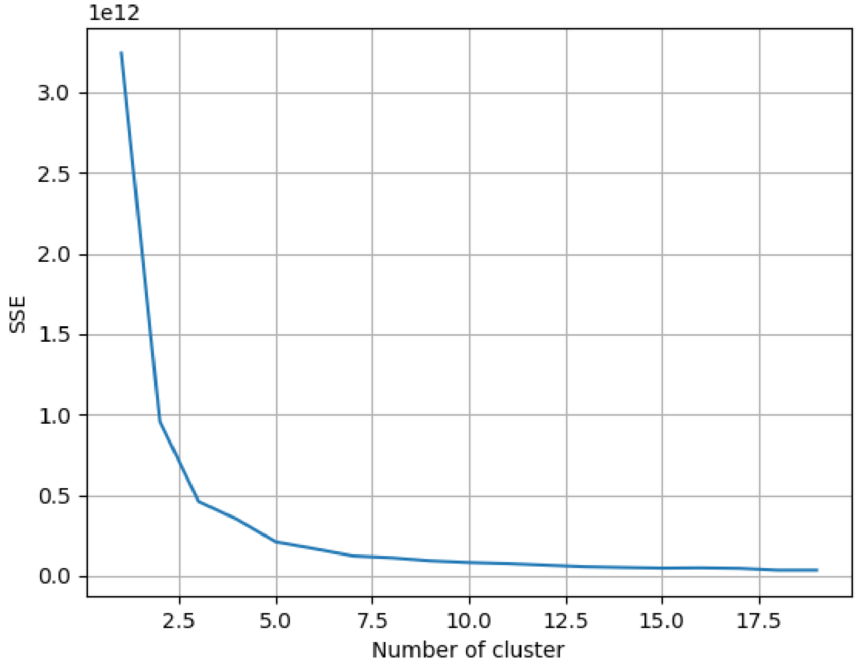


FIGURE 1136. DETERMINATION OF THE OPTIMAL NUMBER OF CLUSTERS FOR THE WASTE DUMPS, BY USING THE ELBOW METHOD.

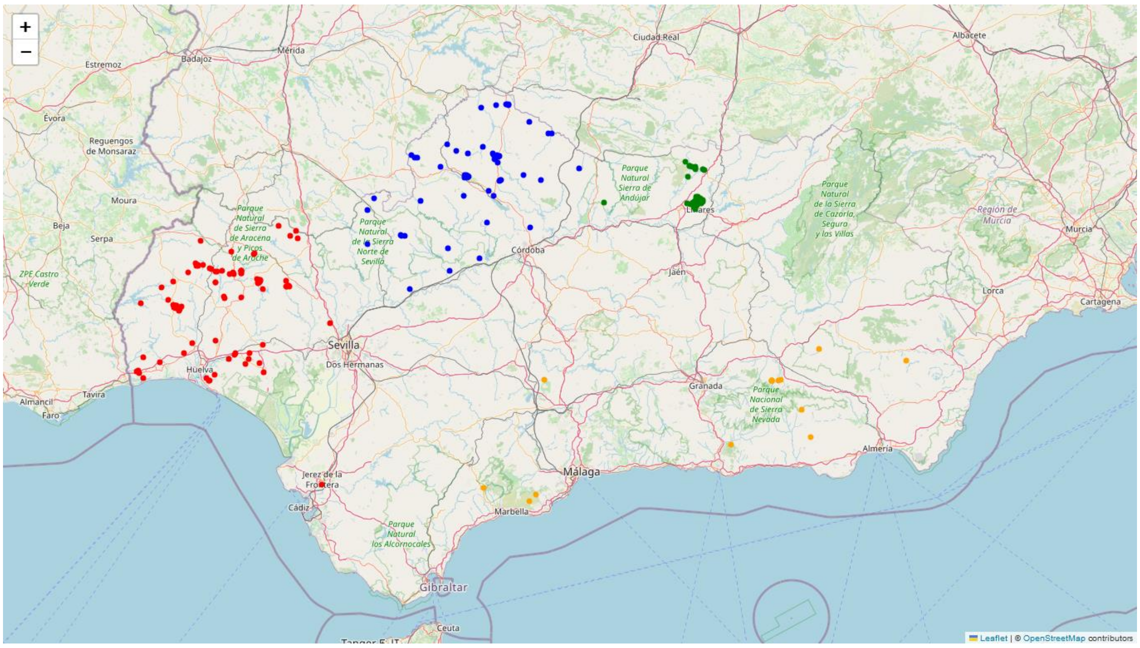


FIGURE 1147. GEO-CLUSTER OF THE AVAILABLE WASTE DUMPS IN THE MINE SITES.

## Biplots

An interesting test that can be performed to the available data and according to the clusters, are the biplots in which any pair of the elements or substances are graphed taking into account such clusters.

It is important to remark that the clusters are not based upon the geographical coordinates but considering the geochemical profiles of the ponds, dams, dumps or pile samples. The following graphs show the results (the digital version allows for an adequate zooming to improve readability.

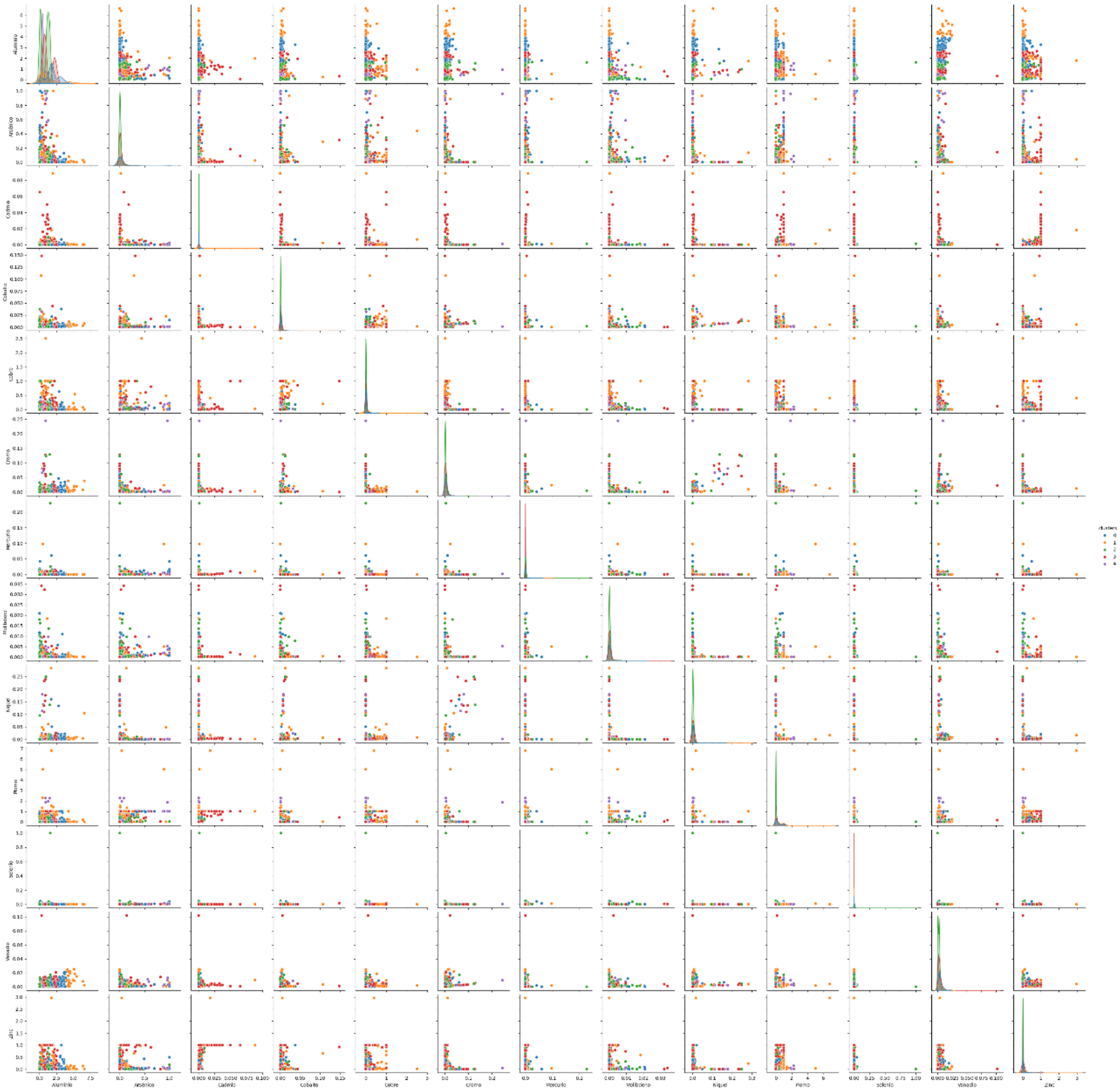

FIGURE 1158. PAIRPLOT CORRESPONDING TO THE WASTE DUMPS SAMPLES (LABORATORY ANALYSIS).

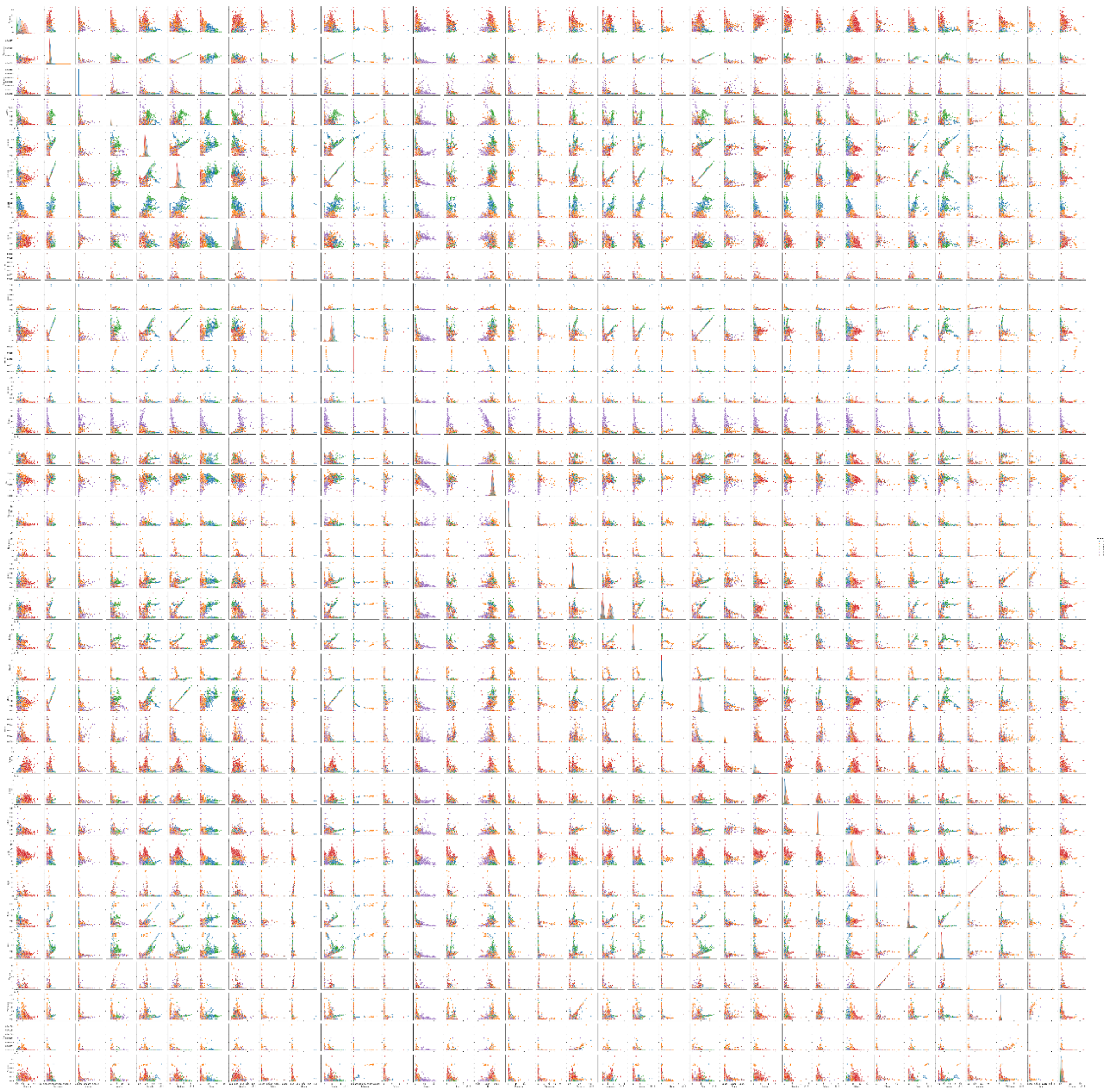

Figure 169. Pairplot of the waste ponds samples (in-situ analysis).

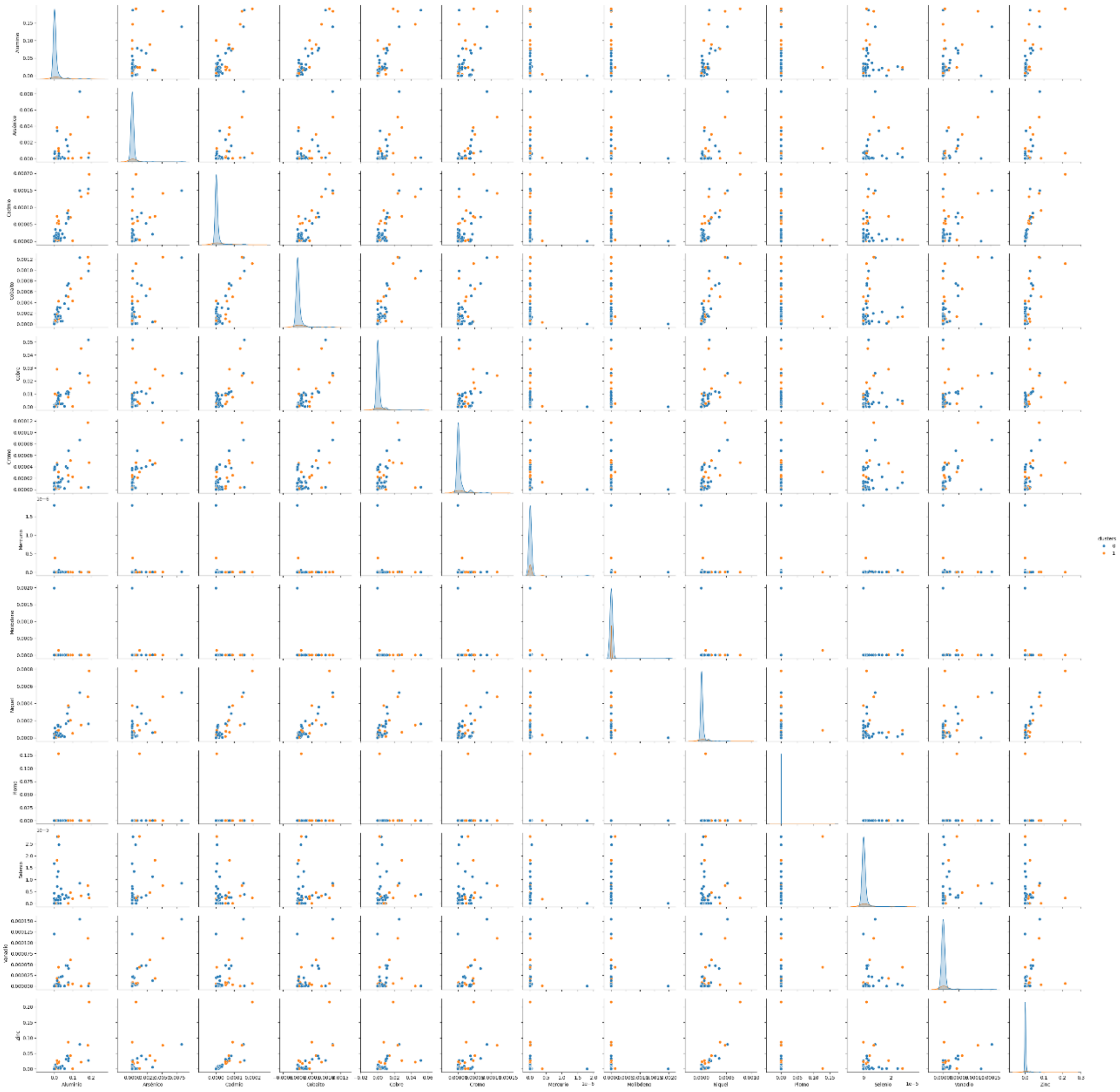

FIGURE 2017. PAIRPLOT OF THE WASTE WATER SAMPLES (IN-SITU ANALYSIS).

## 5.3. Elements Considered and Potential Value

It is important to recall that the analytical data was aggregated for each substance and type of mining waste, and applied to the aggregated volume of the mining waste structures in each location, see the example provided below.

### CRMs and Strategic Elements

According to the latest EU Report on this topic (see [1]), in a preliminary basis the following CRMs have been considered (in dark red the elements discarded at this point):

TABLE 4. CRITICAL AND STRATEGIC RAW MATERIALS [1]

| Element/substance | Type | Element/substance | Type |
|---|---|---|---|
| Aluminum | Critical | Helium | Critical |
| Antimony | Critical | Indium | Critical |
| Arsenic | Critical | Lithium | Critical |
| Baryte | Critical | Magnesium | Critical |
| Bauxite | Critical | Manganese | Critical |
| Beryllium | Critical | Nickel | Strategic |
| Bismuth | Critical | Niobium | Critical |
| Boron (Borate) | Critical | Phosphate Rock | Critical |
| Cobalt | Critical | Phosphorus | Critical |
| Coking Coal | Critical | Platinum Group Metals | Critical |
| Copper | Strategic | Scandium | Critical |
| Feldspar | Critical | Silicon (Silicon Metal) | Critical |
| Fluorspar | Critical | Strontium | Critical |
| Gallium | Critical | Tantalum | Critical |
| Germanium | Critical | Titanium (Titanium Metal) | Critical |
| Graphite (Natural) | Critical | Tungsten | Critical |
| Hafnium | Critical | Vanadium | Critical |

## Additional Valuable Elements and Materials

In addition to the Critical and Strategic RMs, here is a list of other elements and materials that might be valuable from mining waste but are not present in the previous list. These elements are of high interest due to their economic value or specialized uses:

### Precious Metals

- Gold (Au): Often found in tailings from the processing of other minerals, especially in polymetallic ore deposits.
- Silver (Ag): Frequently associated with lead and zinc ores, recoverable from slags and residues.

### Base Metals

- Iron (Fe): Recoverable from tailings and as a byproduct in mining operations focused on other metals.
- Tin (Sn): Found in waste from cassiterite mining or in polymetallic ores.
- Lead (Pb): Can be extracted from old mining dumps, particularly from galena-rich waste.
- Zinc (Zn): Often recoverable from processing residues or low-grade tailings.

### Industrial Minerals

- Silica ($SiO_2$): Found in mine tailings, particularly in waste from the production of feldspar or quartz.
- Gypsum ($CaSO_4{\cdot}2H_2O$): A byproduct from the desulfurization of mine effluents or waste streams.

- Bauxite Residues (Red Mud): Contains valuable alumina and rare earth elements in some cases.

### Energy-related Elements

- Uranium (U): Often found in the byproducts of phosphate or other mining operations.
- Thorium (Th): Present in waste streams of monazite or rare earth extraction processes.

### Recyclable or Reusable Materials

- Carbon Black and Slags: Usable for industrial applications like cement production.
- Phosphogypsum: A byproduct of phosphate mining with potential use in agriculture or construction.
- Limestone and Marble Residues: Recoverable for soil treatment or industrial applications.

### Potential Opportunities from Mining Wastes

There is another interesting aspect: some of these elements and materials might be recovered not only from mining wastes but from other different sources, e.g. slags and residues from iron or steel production, to obtain vanadium and similar elements.

Therefore, these elements and materials are increasingly targeted for extraction due to advancements in tailings reprocessing technologies, driven by sustainability and the circular economy. Recovering valuable elements from waste not only mitigates environmental impacts but also provides an economic incentive for mining companies to revisit old or abandoned mining sites.

## Present Market Price Quotes

A search for present market prices for the previous elements and substances has been performed in some of the main webs available through internet, see the next Table for details. Some of the substances were not located at the present search of data but could be assumed in the future.

TABLE 5. PRESENT MARKET PRICES FOR SELECTED ELEMENTS AND SUBSTANCES ([18], [19], [20], [21])

| Element | Type | CNY/mt | EUR/kg |
|---|---|---|---|
| Aluminium | Critical | 27900 | 3.63 |
| Antimony | Critical | 146000 | 18.98 |
| Arsenic | Critical | 800000 | 104.00 |
| Sulphur | Critical | 690 | 0.09 |
| Bismuth | Critical | 73000 | 9.49 |
| Cadmium | Non-Critical | 35500 | 4.62 |
| Calcium | Non-Critical | 41920 | 5.45 |
| Cobalt | Critical | 190000 | 24.70 |
| Copper | Critical | 74000 | 9.62 |
| Chromium | Non-Critical | 65000 | 8.45 |
| Tin | Non-Critical | 246000 | 31.98 |
| Strontium | Critical | 60000 | 7.80 |
| Phosphorus | Critical | 2121540 | 275.80 |
| Iron | Non-Critical | 800 | 0.10 |

| Element | Type | CNY/mt | EUR/kg |
|---|---|---|---|
| Yttrium | Non-Critical | 247540 | 32.18 |
| LE | Non-Critical | 0 | 0.00 |
| Magnesium | Critical | 200 | 0.03 |
| Manganese | Critical | 12500 | 1.63 |
| Mercury | Non-Critical | 271850 | 35.34 |
| Molybdenum | Non-Critical | 113150 | 14.71 |
| Niobium | Critical | 650000 | 84.50 |
| Nickel | Strategic | 128300 | 16.68 |
| Silver | Non-Critical | 7700000 | 1001.00 |
| Lead | Non-Critical | 17400 | 2.26 |
| Potassium | Non-Critical | 92080 | 11.97 |
| Rubidium | Non-Critical | 104107690 | 13534.00 |
| Selenium | Non-Critical | 200000 | 26.00 |
| Silicon | Critical | 13540 | 1.76 |
| Titanium | Critical | 53000 | 6.89 |
| Thorium | Non-Critical | 1244620 | 161.80 |
| Uranium | Non-Critical | 408460 | 53.10 |
| Vanadium | Critical | 2100000 | 273.00 |
| Wolfram | Critical | 380000 | 49.40 |
| Zinc | Non-Critical | 25800 | 3.35 |
| Zirconium | Non-Critical | 163620 | 21.27 |

Prices for materials like Silica (Quartz) and Gypsum are approximate and can vary based on purity, form, and market conditions. For the most accurate and up-to-date pricing, consulting specialized commodity market reports or industry sources is recommended.

A disclaimer must be set at this point: the prices provided are indicative and subject to change. For real-time pricing, please refer to the respective data sources or financial market platforms.

## Potential Values in Sites

The following step of this research involves the calculation of the (maximum) potential value of the recoverable elements and substances in each one of the target mining waste sites, sharing in this Section some ideas from [4, 7, 11] and adding some other steps to the calculations.

Such potential value does not consider the cost of the obtention of such substances, nor the efficiency of the technology that might be applied. Indeed, the feasibility or the profitability of the required operations is not faced in this preliminary stage of the work. This point will be slightly described later in this report.

In order to address this calculation, a simple algorithm is the following:

1. For each mining waste location:

   a. For each substance or element present in location:
      i. Average element contents in waters (a) and rocks (b).
      ii. Multiply contents by water volumes and rocks, respectively (thus obtaining bulk masses).
      iii. Sum element mass obtained from waters and rocks.
      iv. Store fraction of elements coming from waters or rocks.
      v. Calculate potential value for element or substance.
   b. Sum the potential values for elements present in site.
2. Geographical calculation of potential values for the overall mining waste:
   a. Sum for the total of the region.
   b. Sum for each province.
   c. Sum for each potential area (i.e. for each cluster region).

## 5.4. Potential Revenues: Key Considerations in Reprocessing Mining Wastes

The reprocessing of mining wastes offers an opportunity to recover valuable substances while mitigating environmental impacts. However, the successful implementation of such projects depends on addressing several critical aspects that influence feasibility, efficiency, and sustainability. These considerations span technical, economic, and environmental dimensions.

One of the most important factors is the physical form of the waste. Mining wastes exist in various forms, requiring different technologies for their treatment, including:

- Wastewater, which usually demands technologies such as filtration, ion exchange, or chemical precipitation.
- Mine tailings and sludges, often involve physical separation, flotation, or leaching processes.
- Waste rocks, being solid and bulky, pose different logistical and processing challenges compared to fine-grained tailings.

The chemical composition of the waste is equally critical. Understanding the concentrations of target elements and the presence of impurities determines the selection of recovery methods and their economic viability. For example, high concentrations of valuable metals like gold, silver, or cobalt can justify intensive processing, whereas the presence of hazardous elements such as arsenic or mercury requires careful handling.

Other factors include:

- Environmental Impact: Waste reprocessing should align with environmental regulations, ensuring reduced ecological footprints and compliance with sustainability goals. This aspect has not been considered in the present work
- Economic Feasibility: Market demand, commodity prices, and recovery costs play a pivotal role in determining the profitability of reprocessing efforts. The feasibility is a key aspect in the conceptual design of a project, even in its preliminary stages, even if a noticeable uncertainty can be introduced in the calculations.
- Technology Availability: Access to advanced technologies, such as bioleaching or hydrometallurgy, is essential for efficient extraction from complex matrices. This aspect exceeds the limit of this research, so one assumes that the technology or technologies are available to the targets of the project.
- Infrastructure and Logistics: Proximity to processing facilities, energy sources, and transportation networks significantly affect the practicality of reprocessing. It is a very interesting and crucial variable. It is extremely important to take care of:
    - Difference between straight line and road line distances between any couple on points in the area.
    - Energy plants availability is crucial and usually can be a restriction aspect in desert areas.

- Mining waste plants are not very movable infrastructures, so the locations and typologies of the plant treatment network should also be optimized during the project detail planning stage.

Overall, mining waste reprocessing requires a multidisciplinary approach, balancing technical capabilities, environmental stewardship, and economic returns. By considering these factors, industries can maximize resource recovery while addressing legacy waste challenges.

## Estimated Recovery and Cost Figures by Technology and Waste Types

This aspect is of the highest interest. Nevertheless, it is a very complicated question, so the data applied is merely indicative. The potential revenues of reprocessing the mining waste have to consider the following aspects:

- Estimating the partial cost of treatment of mine waters containing particulate or dissolved elements and substances. This cost is established for a certain unit (i.e. $m^3$ for liquid stuff and tons for solids and muds). The units would be EUR/$m^3$ or EUR/t.
- Giving a value for mean recovery (i.e. efficiency, that is the fraction of the total amount of the element or substance that can be effectively retained). Another way of facing this parameter is fixing the amount of residual element that is not likely to be recovered.

To estimate the cost of treating the three types of waste, some assumptions must be made due to the lack of specific data on unit costs. Below, some assumptions are proposed, and calculations are performed.

### General Assumptions

Transportation Costs

- Transportation rate: €0.05 per ton-kilometer (€/t·km) for solid materials.
- For liquids (aqueous waste): €0.07 per ton-kilometer due to the need for specialized equipment.

Treatment Costs

- Aqueous waste: €8 per cubic meter (€/m³).
- Tailings from metallurgical processing: €12/m³.
- Fractured rock: €20/m³.

Post-Treatment Waste Management Costs

- Unified rate: €3 per ton for all types of waste.

### Provided Data

Densities:

- Aqueous waste: 1 t/m³.
- Tailings: 3 t/m³.
- Fractured rock: 2 t/m³.

Transportation Distances

- Aqueous waste: Assumed to have the same distance as tailings (1 km) if not specified.
- Tailings: 1 km to the treatment plant, 3 km to the final disposal site.
- Fractured rock: 3 km to the treatment plant, 3 km to the final disposal site.

### Calculations by Waste Type

1. Aqueous Waste (Dams)

a. Transportation Cost to Treatment Plant:

- Weight per m³: 1 t/m³.
- Distance: 1 km.

- Cost: 1 t/m³ × 1 km × €0.07/t·km = €0.07/m³.

b. Treatment Cost:

- Cost: €8/m³.

c. Post-Treatment Waste Management Cost:

- Weight per m³: 1 t/m³.
- Distance to final disposal: 3 km.
- Transportation cost to disposal site: 1 t × 3 km × €0.07/t·km = €0.21/m³.
- Management cost: 1 t × €3/t = €3/m³.
- Total management cost: 0.21 + 3 = €3.21/m³.

d. Total Cost per m³: 0.07 + 8 + 3.21 = €11.28/m³.

2. Tailings from Metallurgical Processing (Ponds):

a. Transportation Cost to Treatment Plant:

- Weight per m³: 3 t/m³.
- Distance: 1 km.
- Cost: 3 t/m³ × 1 km × €0.05/t·km = €0.15/m³.

b. Treatment Cost:

- Cost: €12/m³.

c. Post-Treatment Waste Management Cost:

- Weight per m³: 3 t/m³.
- Distance to final disposal: 3 km.
- Transportation cost to disposal site: 3 t × 3 km × €0.05/t·km = €0.45/m³.
- Management cost: 3 t × €3/t = €9/m³.
- Total management cost: 0.45 + 9 = €9.45/m³.

d. Total Cost per m³: 0.15 + 12 + 9.45 = €21.60/m³.

3. Fractured Rock (Waste Dumps and Stockpiles):

a. Transportation Cost to Treatment Plant:

- Weight per m³: 2 t/m³.
- Distance: 3 km.
- Cost: 2 t/m³ × 3 km × €0.05/t·km = €0.30/m³.

b. Treatment Cost:

- Cost: €20/m³.

c. Post-Treatment Waste Management Cost:

- Weight per m³: 2 t/m³.
- Distance to final disposal: 3 km.
- Transportation cost to disposal site: 2 t × 3 km × €0.05/t·km = €0.30/m³.
- Management cost: 2 t × €3/t = €6/m³.
- Total management cost: 0.30 + 6 = €6.30/m³.

d. Total Cost per m³: 0.30 + 20 + 6.30 = €26.60/m³.

## Summary of Total Costs per Cubic Meter

- Aqueous Waste: €11.28/m³
- Tailings: €21.60/m³
- Fractured Rock: €26.60/m³

## Notes and Considerations

- Transportation and treatment costs may vary depending on local conditions and market prices.
- Post-treatment waste management costs include both transportation to the disposal site and disposal fees.

## Revenue Calculations

According to the previous section, let $CT_{i,j}$ be the cost of treatment for the element "i", given a certain kind of mining waste "j".

As well, let MRi,j be the mean recovery for the element "i", given a certain kind of mining waste "j".

Then, if one has a certain amount of mining waste, let's say $MW_{i,j}$, then, the potential recovery $PR_{i,j}$ of a substance i in a waste j will be:

$$PR_{i,j} = MW_{i,j} \cdot MR_{i,j}$$

And the partial cost ($PC_{i,j}$) associated to such a recovery will be:

$$PC_{i,j} = MW_{i,j} \cdot CT_{i,j}$$

Being the total cost associated to that:

$$PC_k = \sum_{i=1}^{n} PC_{i,j}$$

Hence, considering the potential value of the substance or element $PV_i$, since this value does not depend on its physical form:

$$PV_i = \sum_{j=1}^{m} PR_{i,j} \cdot MP_i$$

Where j is the type of residue and m is the total number of forms of the residues (waters, rocks, muds or tailings, if available).

For a certain site k, one can give the total amount of the substances or elements present in it as:

$$PV_k = \sum_{i=1}^{n} PV_{i,j}$$

And finally, the total revenues for a certain area q, where p sites are present, would be:

$$TR_q = \sum_{k=1}^{p} (PV_k - PC_k)$$

## Results

This section includes the results obtained following the above methodology. Some parameters have been derived from a number of assumptions that could represent some sort of average in many of the mine sites in the region.

The recovery of the waste treatment processed was assumed to be 60% in ponds, 40% in dams, 80% in waste dumps and 90% in piles (assuming that the piles stocks have better mineral qualities than the waste structures).

The results have been obtained by direct calculations over the bulk data. Since the number of sites is rather high (near 4000) and many of them have no data or the turnover is very low, the results have been ranked.

The following table summarizes the results for the first 50 mine sites, including:

- Accumulated Potential Value (MEUR), summing the potential value of all the substances in all the waste structures of the site. The sites lacking waste volume data were removed from the calculations.
- Waste Volume ($m^3$), for the different kinds of waste structures and ranking by the total volume.

- Waste Treatment Cost (MEUR), by applying the criteria and procedure shown before.
- Potential Recoverable Value (MEUR), by considering the fractions of recovered substances, depending on the type of waste.
- Potential Revenue (MEUR), by substracting the costs from the potential recoverable value.

## Discussion

It is very important to consider that the data used is very weak, compared to the amount of data that would be required to characterize any mine site with aims of mine exploitation under positive revenue conditions.The data includes the mine site coordinates, estimations of area, volume and kind of waste structures.

The waste treatment unit costs were obtained by applying some standard costs observed in some existent operations.

This fact is merely preliminary at this point, but it is also the usual procedure in terms of pre-viability studies, which are applied in the very first steps in analyzing any mining operation.

Under this point of view the results may be acceptable. Nevertheless, in some cases the initial data corresponding to some of the mine sites should be revisited.

In other words, the most important mine sites in this study, showing the highest potential for their future exploitation, should include a preliminary phase in order to confirm the validity of the data and complement such data with some additional field campaign.

Disclaimer on Data Analysis Results

To fully understand the information presented in Tables 6, 7, 8, 9, and 10, it is essential to consider the following:

- The potential of each deposit has been assessed based on a limited number of data points.
- There is a degree of uncertainty in various parameters, values, analyses, and processes.
- The analysis of the provided data (Andalusia) offers only a preliminary indication of which deposits are candidates for a more in-depth exploration and which are less promising. At this stage, no deposit has sufficient information to allow for reliable characterization.
- The data in the afore-mentioned tables should be regarded as illustrative of the type of conclusions that could be drawn if sufficient information were available to characterize the mining waste deposits.
- The potential values presented in the tables should be interpreted as relative classifications rather than absolute figures.

TABLE 6: ACCUMULATES POTENTIAL VALUE

| SITE NUMBER | ACCCUMULATED POTENTIAL VALUE (MEUR) | | | | TOTAL |
|---|---|---|---|---|---|
| | Dams | Ponds | Tailings | Basins | |
| 1132 | 15480 | 0 | 2327 | 0 | 17807 |
| 1553 | 13444 | 0 | 0 | 0 | 13444 |
| 1194 | 7842 | 0 | 0 | 0 | 7842 |
| 1571 | 6374 | 0 | 0 | 0 | 6374 |
| 1980 | 0 | 0 | 5054 | 0 | 5054 |
| 1315 | 0 | 0 | 2072 | 0 | 2072 |
| 127 | 0 | 0 | 2044 | 0 | 2044 |
| 2545 | 696 | 0 | 0 | 0 | 696 |
| 1294 | 0 | 0 | 883 | 0 | 883 |
| 1669 | 11 | 0 | 0 | 808 | 819 |
| 1439 | 493 | 0 | 0 | 0 | 493 |
| 1427 | 423 | 0 | 0 | 0 | 423 |
| 1136 | 0 | 0 | 535 | 0 | 535 |
| 1367 | 0 | 0 | 464 | 0 | 464 |
| 94 | 0 | 0 | 426 | 0 | 426 |
| 1212 | 306 | 0 | 0 | 0 | 306 |
| 1490 | 0 | 0 | 400 | 0 | 400 |
| 1670 | 0 | 0 | 0 | 366 | 366 |
| 1338 | 62 | 0 | 219 | 0 | 282 |
| 2337 | 0 | 0 | 269 | 0 | 269 |
| 3831 | 0 | 0 | 111 | 162 | 273 |
| 704 | 0 | 0 | 213 | 0 | 213 |
| 748 | 152 | 0 | 10 | 0 | 162 |
| 1605 | 148 | 0 | 12 | 0 | 160 |
| 1331 | 0 | 0 | 191 | 17 | 207 |
| 1522 | 0 | 0 | 203 | 0 | 203 |
| 1369 | 0 | 0 | 190 | 0 | 190 |
| 1429 | 136 | 0 | 0 | 0 | 136 |
| 1287 | 0 | 0 | 171 | 0 | 171 |
| 1940 | 0 | 0 | 143 | 0 | 143 |
| 1282 | 0 | 0 | 134 | 0 | 134 |
| 1077 | 0 | 0 | 130 | 0 | 130 |
| 756 | 0 | 0 | 123 | 0 | 123 |
| 3499 | 0 | 0 | 123 | 0 | 123 |
| 1424 | 0 | 0 | 122 | 0 | 122 |
| 1314 | 2 | 0 | 118 | 0 | 120 |
| 1365 | 0 | 0 | 117 | 0 | 117 |
| 3834 | 80 | 0 | 0 | 0 | 80 |
| 1978 | 0 | 0 | 103 | 0 | 103 |
| 659 | 0 | 0 | 95 | 0 | 95 |
| 153 | 0 | 0 | 84 | 0 | 84 |
| 1310 | 0 | 0 | 82 | 0 | 82 |
| 211 | 0 | 0 | 78 | 0 | 78 |
| 627 | 0 | 0 | 73 | 0 | 73 |
| 1173 | 0 | 0 | 69 | 0 | 69 |
| 3612 | 0 | 0 | 66 | 0 | 66 |
| 8 | 0 | 0 | 64 | 0 | 64 |
| 2330 | 0 | 0 | 63 | 0 | 63 |

TABLE 7: WASTE VOLUME

| SITE NUMBER | WASTE VOLUME M3 | | | | |
|---|---|---|---|---|---|
| | Dams | Ponds | Tailings | Basins | TOTAL |
| 1132 | 205747175 | 0 | 157071288 | 0 | 362818463 |
| 1980 | 0 | 0 | 134500000 | 0 | 134500000 |
| 1212 | 581972 | 0 | 127751047 | 0 | 128333019 |
| 2677 | 0 | 51869253 | 0 | 0 | 51869253 |
| 1553 | 32100319 | 0 | 12856 | 0 | 32113174 |
| 3510 | 0 | 0 | 25181910 | 0 | 25181910 |
| 3509 | 0 | 0 | 24721030 | 0 | 24721030 |
| 1488 | 0 | 0 | 21686490 | 0 | 21686490 |
| 1359 | 0 | 0 | 19872936 | 0 | 19872936 |
| 3499 | 0 | 0 | 16089150 | 0 | 16089150 |
| 3858 | 0 | 0 | 15955603 | 0 | 15955603 |
| 127 | 0 | 0 | 13179458 | 0 | 13179458 |
| 1468 | 0 | 0 | 12483400 | 0 | 12483400 |
| 1194 | 11193698 | 0 | 0 | 0 | 11193698 |
| 1571 | 10763018 | 0 | 3400 | 0 | 10766418 |
| 1422 | 10504560 | 0 | 0 | 0 | 10504560 |
| 1315 | 0 | 0 | 10214352 | 0 | 10214352 |
| 1367 | 0 | 0 | 9433464 | 0 | 9433464 |
| 1294 | 0 | 0 | 9351935 | 0 | 9351935 |
| 1669 | 16901 | 0 | 0 | 6936118 | 6953019 |
| 94 | 0 | 0 | 6277256 | 0 | 6277256 |
| 1672 | 0 | 0 | 6198168 | 0 | 6198168 |
| 1490 | 0 | 0 | 6117360 | 0 | 6117360 |
| 2337 | 0 | 0 | 5143500 | 0 | 5143500 |
| 1077 | 0 | 0 | 4744730 | 0 | 4744730 |
| 1136 | 0 | 0 | 4709146 | 0 | 4709146 |
| 3508 | 0 | 0 | 4683000 | 0 | 4683000 |
| 704 | 0 | 0 | 4107451 | 0 | 4107451 |
| 1282 | 0 | 0 | 3410220 | 0 | 3410220 |
| 3831 | 0 | 0 | 1448301 | 1879101 | 3327402 |
| 1338 | 76703 | 0 | 2796998 | 0 | 2873702 |
| 1940 | 0 | 0 | 2566048 | 0 | 2566048 |
| 1331 | 0 | 0 | 2349376 | 180750 | 2530126 |
| 1520 | 0 | 0 | 2459296 | 0 | 2459296 |
| 2060 | 0 | 0 | 2300000 | 0 | 2300000 |
| 1522 | 0 | 0 | 2221428 | 0 | 2221428 |
| 3515 | 0 | 0 | 2147303 | 0 | 2147303 |
| 673 | 0 | 2128207 | 0 | 0 | 2128207 |
| 2541 | 0 | 0 | 2100000 | 0 | 2100000 |
| 1670 | 0 | 0 | 0 | 1866109 | 1866109 |
| 1302 | 0 | 0 | 1807824 | 0 | 1807824 |
| 661 | 0 | 1591820 | 0 | 0 | 1591820 |
| 659 | 0 | 0 | 1455340 | 0 | 1455340 |
| 1371 | 0 | 0 | 1351839 | 0 | 1351839 |
| 1424 | 0 | 0 | 1320048 | 0 | 1320048 |
| 1369 | 0 | 0 | 1297199 | 0 | 1297199 |
| 1287 | 0 | 0 | 1221448 | 0 | 1221448 |
| 2370 | 0 | 0 | 1193088 | 0 | 1193088 |

TABLE 8: WASTE TREATMENT COST

| SITE NUMBER | WASTE TREATMENT COST (MEUR) | | | | |
|---|---|---|---|---|---|
| | Dams | Ponds | Tailings | Basins | TOTAL |
| 1132 | 4444 | 0 | 4178 | 0 | 8622 |
| 1980 | 0 | 0 | 3578 | 0 | 3578 |
| 1212 | 13 | 0 | 3398 | 0 | 3411 |
| 2677 | 0 | 585 | 0 | 0 | 585 |
| 1553 | 693 | 0 | 0 | 0 | 694 |
| 3510 | 0 | 0 | 670 | 0 | 670 |
| 3509 | 0 | 0 | 658 | 0 | 658 |
| 1488 | 0 | 0 | 577 | 0 | 577 |
| 1359 | 0 | 0 | 529 | 0 | 529 |
| 3499 | 0 | 0 | 428 | 0 | 428 |
| 3858 | 0 | 0 | 424 | 0 | 424 |
| 127 | 0 | 0 | 351 | 0 | 351 |
| 1468 | 0 | 0 | 332 | 0 | 332 |
| 1194 | 242 | 0 | 0 | 0 | 242 |
| 1571 | 232 | 0 | 0 | 0 | 233 |
| 1422 | 227 | 0 | 0 | 0 | 227 |
| 1315 | 0 | 0 | 272 | 0 | 272 |
| 1367 | 0 | 0 | 251 | 0 | 251 |
| 1294 | 0 | 0 | 249 | 0 | 249 |
| 1669 | 0 | 0 | 0 | 185 | 185 |
| 94 | 0 | 0 | 167 | 0 | 167 |
| 1672 | 0 | 0 | 165 | 0 | 165 |
| 1490 | 0 | 0 | 163 | 0 | 163 |
| 2337 | 0 | 0 | 137 | 0 | 137 |
| 1077 | 0 | 0 | 126 | 0 | 126 |
| 1136 | 0 | 0 | 125 | 0 | 125 |
| 3508 | 0 | 0 | 125 | 0 | 125 |
| 704 | 0 | 0 | 109 | 0 | 109 |
| 1282 | 0 | 0 | 91 | 0 | 91 |
| 3831 | 0 | 0 | 39 | 50 | 89 |
| 1338 | 2 | 0 | 74 | 0 | 76 |
| 1940 | 0 | 0 | 68 | 0 | 68 |
| 1331 | 0 | 0 | 62 | 5 | 67 |
| 1520 | 0 | 0 | 65 | 0 | 65 |
| 2060 | 0 | 0 | 61 | 0 | 61 |
| 1522 | 0 | 0 | 59 | 0 | 59 |
| 3515 | 0 | 0 | 57 | 0 | 57 |
| 673 | 0 | 24 | 0 | 0 | 24 |
| 2541 | 0 | 0 | 56 | 0 | 56 |
| 1670 | 0 | 0 | 0 | 50 | 50 |
| 1302 | 0 | 0 | 48 | 0 | 48 |
| 661 | 0 | 18 | 0 | 0 | 18 |
| 659 | 0 | 0 | 39 | 0 | 39 |
| 1371 | 0 | 0 | 36 | 0 | 36 |
| 1424 | 0 | 0 | 35 | 0 | 35 |
| 1369 | 0 | 0 | 35 | 0 | 35 |
| 1287 | 0 | 0 | 32 | 0 | 32 |
| 2370 | 0 | 0 | 32 | 0 | 32 |

TABLE 9: POTENTIAL RECOVERABLE VALUE

| SITE NUMBER | POTENTIAL RECOVERABLE VALUE (MEUR) | | | | |
|---|---|---|---|---|---|
| | Dams | Ponds | Tailings | Basins | TOTAL |
| 1132 | 15480 | 0 | 2327 | 0 | 17807 |
| 1553 | 13444 | 0 | 0 | 0 | 13444 |
| 1194 | 7842 | 0 | 0 | 0 | 7842 |
| 1571 | 6374 | 0 | 0 | 0 | 6374 |
| 1980 | 0 | 0 | 5054 | 0 | 5054 |
| 1315 | 0 | 0 | 2072 | 0 | 2072 |
| 127 | 0 | 0 | 2044 | 0 | 2044 |
| 2545 | 696 | 0 | 0 | 0 | 696 |
| 1294 | 0 | 0 | 883 | 0 | 883 |
| 1669 | 11 | 0 | 0 | 808 | 819 |
| 1439 | 493 | 0 | 0 | 0 | 493 |
| 1427 | 423 | 0 | 0 | 0 | 423 |
| 1136 | 0 | 0 | 535 | 0 | 535 |
| 1367 | 0 | 0 | 464 | 0 | 464 |
| 94 | 0 | 0 | 426 | 0 | 426 |
| 1212 | 306 | 0 | 0 | 0 | 306 |
| 1490 | 0 | 0 | 400 | 0 | 400 |
| 1670 | 0 | 0 | 0 | 366 | 366 |
| 1338 | 62 | 0 | 219 | 0 | 282 |
| 2337 | 0 | 0 | 269 | 0 | 269 |
| 3831 | 0 | 0 | 111 | 162 | 273 |
| 704 | 0 | 0 | 213 | 0 | 213 |
| 748 | 152 | 0 | 10 | 0 | 162 |
| 1605 | 148 | 0 | 12 | 0 | 160 |
| 1331 | 0 | 0 | 191 | 17 | 207 |
| 1522 | 0 | 0 | 203 | 0 | 203 |
| 1369 | 0 | 0 | 190 | 0 | 190 |
| 1429 | 136 | 0 | 0 | 0 | 136 |
| 1287 | 0 | 0 | 171 | 0 | 171 |
| 1940 | 0 | 0 | 143 | 0 | 143 |
| 1282 | 0 | 0 | 134 | 0 | 134 |
| 1077 | 0 | 0 | 130 | 0 | 130 |
| 756 | 0 | 0 | 123 | 0 | 123 |
| 3499 | 0 | 0 | 123 | 0 | 123 |
| 1424 | 0 | 0 | 122 | 0 | 122 |
| 1314 | 2 | 0 | 118 | 0 | 120 |
| 1365 | 0 | 0 | 117 | 0 | 117 |
| 3834 | 80 | 0 | 0 | 0 | 80 |
| 1978 | 0 | 0 | 103 | 0 | 103 |
| 659 | 0 | 0 | 95 | 0 | 95 |
| 153 | 0 | 0 | 84 | 0 | 84 |
| 1310 | 0 | 0 | 82 | 0 | 82 |
| 211 | 0 | 0 | 78 | 0 | 78 |
| 627 | 0 | 0 | 73 | 0 | 73 |
| 1173 | 0 | 0 | 69 | 0 | 69 |
| 3612 | 0 | 0 | 66 | 0 | 66 |
| 8 | 0 | 0 | 64 | 0 | 64 |
| 2330 | 0 | 0 | 63 | 0 | 63 |

TABLE 10: POTENTIAL REVENUE

| SITE NUMBER | POTENTIAL REVENUE (MEUR) | | | | |
|---|---|---|---|---|---|
| | Dams | Ponds | Tailings | Basins | TOTAL |
| 1553 | 12751 | 0 | 0 | 0 | 12751 |
| 1132 | 11036 | 0 | -1851 | 0 | 9185 |
| 1194 | 7600 | 0 | 0 | 0 | 7600 |
| 1571 | 6141 | 0 | 0 | 0 | 6141 |
| 1315 | 0 | 0 | 1801 | 0 | 1801 |
| 127 | 0 | 0 | 1693 | 0 | 1693 |
| 1980 | 0 | 0 | 1476 | 0 | 1476 |
| 2545 | 671 | 0 | 0 | 0 | 671 |
| 1294 | 0 | 0 | 635 | 0 | 635 |
| 1669 | 11 | 0 | 0 | 623 | 634 |
| 1439 | 479 | 0 | -9 | 0 | 470 |
| 1427 | 416 | 0 | 0 | 0 | 416 |
| 1136 | 0 | 0 | 409 | 0 | 409 |
| 1670 | 0 | 0 | 0 | 316 | 316 |
| 94 | 0 | 0 | 259 | 0 | 259 |
| 1490 | 0 | 0 | 238 | 0 | 238 |
| 1367 | 0 | 0 | 213 | 0 | 213 |
| 1338 | 61 | 0 | 145 | 0 | 206 |
| 3831 | 0 | 0 | 73 | 112 | 185 |
| 748 | 150 | 0 | 7 | 0 | 157 |
| 1369 | 0 | 0 | 156 | 0 | 156 |
| 1605 | 145 | 0 | 6 | 0 | 151 |
| 1522 | 0 | 0 | 144 | 0 | 144 |
| 1331 | 0 | 0 | 128 | 12 | 140 |
| 1287 | 0 | 0 | 138 | 0 | 138 |
| 2337 | 0 | 0 | 132 | 0 | 132 |
| 1429 | 131 | 0 | 0 | 0 | 131 |
| 704 | 0 | 0 | 104 | 0 | 104 |
| 1314 | 2 | 0 | 100 | 0 | 102 |
| 756 | 0 | 0 | 94 | 0 | 94 |
| 1365 | 0 | 0 | 89 | 0 | 89 |
| 1424 | 0 | 0 | 87 | 0 | 87 |
| 1978 | 0 | 0 | 76 | 0 | 76 |
| 1940 | 0 | 0 | 75 | 0 | 75 |
| 3834 | 77 | 0 | -2 | 0 | 75 |
| 211 | 0 | 0 | 61 | 0 | 61 |
| 1310 | 0 | 0 | 59 | 0 | 59 |
| 153 | 0 | 0 | 58 | 0 | 58 |
| 659 | 0 | 0 | 56 | 0 | 56 |
| 1173 | 0 | 0 | 49 | 0 | 49 |
| 8 | 0 | 0 | 48 | 0 | 48 |
| 1563 | 0 | 0 | 45 | 0 | 45 |
| 627 | 0 | 0 | 44 | 0 | 44 |
| 1617 | 37 | 0 | 7 | 0 | 44 |
| 1282 | 0 | 0 | 43 | 0 | 43 |
| 3612 | 0 | 0 | 43 | 0 | 43 |
| 2645 | 0 | 0 | 37 | 0 | 37 |
| 2339 | 0 | 0 | 35 | 0 | 35 |

# 6. Conclusions

This report has highlighted the vast potential for mining waste valorization in the regions of Portugal and Spain, focusing on Andalucía, Castilla y León, Extremadura, and Alentejo. By examining regulatory frameworks, mining industry overviews, employment and safety, and the potential recovery of valuable materials, the study demonstrates how mining waste can transition from being an environmental liability to a valuable resource. Despite its promising findings, the research also underscores significant challenges, particularly the lack of comprehensive data for certain regions, which could impede future valorization efforts.

So, this report is considered as a guide on how to manage mine waste for potential CRMs exploitation, as well as an example of best practices and necessary challenges to be reached to better know the real potential of mining wastes in Europe to provide additional supply of CRMs.

## 6.1. Key Achievements

The analysis has revealed several notable achievements and opportunities:

- Regulatory Alignment: Both Portugal and Spain have robust legislative frameworks (Decreto-Lei n.º 10/2010 and RD 975/2009) that align with EU Directive 2006/21/EC [23]. These frameworks provide strong foundations for sustainable mining waste management, emphasizing environmental protection, waste reduction, and safety.
- Economic Potential: Mine waste in Andalucía, Castilla y León, Extremadura, and in Portugal the Alentejo and Norte regions hold significant quantities of mineral wastes that could contain critical raw materials (CRMs) and other valuable substances like gold, silver, and industrial minerals. Recovering these resources can support EU strategies for energy transition and technological autonomy while boosting local economies.
- Safety and Employment Improvements: Over the past decades, the mining sectors in these regions have witnessed remarkable advances in employment conditions, workplace safety, and accident prevention. These improvements have fostered a more sustainable and socially responsible mining industry.
- Data Integration and Clustering: The use of advanced clustering techniques is adequate for the identification of high-potential sites for waste valorization, particularly in Andalucía, where comprehensive data from the IMINA project offers a detailed inventory of mining waste deposits.

## 6.2. Challenges Identified

While the findings are promising, several challenges require urgent attention to ensure the successful implementation of mining waste valorization strategies:

### Data Gaps

- Alentejo: Despite its rich mining history, the lack of detailed data hinders a comprehensive assessment of its mining waste potential.
- Castilla y León and Extremadura: Both regions suffer from fragmented and outdated datasets, which limit the ability to accurately quantify the economic and environmental potential of their mining wastes. For example, databases in Castilla y León require significant reforms and integration before they can be effectively utilized.
- Comparative Disparity: The data richness in Andalucía starkly contrasts with the limited information available for the other regions. This disparity could lead to uneven development and missed opportunities in less-documented areas.
- An intensive exploration campaign is needed in all the regions to better know the mining waste deposits and their potential.

### Technological and Economic Barriers

The recovery of CRMs and other valuable materials from mining wastes often involves high costs and complex technologies, such as bioleaching and hydrometallurgy. Without targeted investment and innovation, some valorization projects may prove economically unviable.

### Infrastructure and Logistics

The proximity of waste deposits to processing plants, energy sources, and transportation networks significantly influences the feasibility of reprocessing operations. Regions with underdeveloped infrastructure face additional barriers to waste valorization.

### Environmental Considerations

Although the valorization of mining wastes can mitigate environmental impacts, improper handling or inadequate technologies could lead to further contamination or ecological damage. Strict adherence to sustainability goals and regulatory frameworks is critical.

## 6.3. Future Directions

To address the identified challenges and fully unlock the potential of mining waste valorization, the following actions are recommended:

### Data Collection and Integration

Conduct comprehensive surveys and sampling campaigns (exploration) in Alentejo, Castilla y León, and Extremadura to fill data gaps. Harmonize existing datasets into a unified framework that facilitates analysis and decision-making.

Once a first exploration campaign will be developed, then a secondary campaign should be implemented focused in the areas where positive results have been provided by the first campaign, also in Andalucía.

### Technological Innovation

Invest in the development and deployment of advanced recovery technologies to improve efficiency and reduce costs. Collaborative efforts between industry, academia, and government can accelerate innovation in this field.

### Regional Collaboration

Promote interregional partnerships to share knowledge, resources, and best practices. Andalucía's success in data integration and waste management could serve as a model for other regions.

### Policy and Incentives

Develop policies and financial incentives to attract private investment in mining waste valorization projects. Public-private partnerships can play a crucial role in overcoming economic barriers.

### Sustainability and Community Engagement

Ensure that valorization projects align with environmental sustainability goals and involve local communities in planning and decision-making. Transparent communication can build public trust and support.

## 6.4. Final Conclusion

This report underscores the significant opportunities for mining waste valorization in Portugal and Spain, particularly in Andalucía, Castilla y León, Extremadura, and Alentejo. However, the success of these initiatives hinges on overcoming critical challenges, most notably the lack of comprehensive data in some regions. By addressing these gaps and fostering innovation, collaboration, and sustainability, mining waste valorization can contribute to the EU's strategic objectives, regional economic development, and environmental resilience. This vision requires a concerted effort from all stakeholders to transform the challenges of today into the opportunities of tomorrow.

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