I4-GREEN
Review of Sustainable Practices
D5.2
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Glossary	
Acronym	Meaning
SMEs	Small and Medium size Enterprises
EU	European Union
EIA	Environmental Impact Assessment
CSR	Corporate Social Responsibility
SoA	State of the Art
MSF	Multi-Stage Flash distillation
MED	Multi-Effect Distillation
ZLD	Zero-Liquid Discharge
NOx	Nitrogen Oxides
IoT	Internet of Things
AI	Artificial Intelligence
CCS	Carbon Capture and Storage
LCA	Life-Cycle Assessment
SLO	Social License to Operate
REEs	Rare Earth Elements
PGMs	Platinum-Group Metals

Executive summary

Task 5.3 Integration of circular & sustainability practices within SMEs focuses on the identification, dissemination, knowledge-exchange and integration of sustainable practices and the latest technological developments in sustainable mining into small and medium-sized enterprises (SMEs).

Subtask 1 (Sustainable practices), for which this review is developed, aims to support the integration of sustainable practices through the review and selection of circular and sustainability practices and tools that can be effectively introduced to SMEs in the regions covered by the I4-GREEN project.

This document provides a review of the political context at the European and national levels, and of the main technologies available to drive sustainability in mining. Several cases in the I4-GREEN regions and beyond are examined, and an analysis and recommendations are made for the integration of these practices within European SMEs.

1. Introduction

The mining industry is increasingly focusing on circular and sustainable practices to minimize environmental impact and enhance resource efficiency. Sustainable mining practices offer significant environmental benefits, including reduced land degradation, lower emissions, and improved biodiversity. Economically, these practices can lead to cost savings, increased resource recovery, and enhanced market competitiveness. It also fosters social acceptance and positive public opinion, while creating a safer environment for workers and local communities, encouraging greater interaction between them, policy makers and mining companies.

This report examines several sources to identify the latest technology and technique developments, building on real-life applications and outputs from key projects such as the European project MIREU, the Interreg project REMIX and ERAMIN2 project REVIVING.

1.1. Objectives & Methodology

A review of existing databases and resources was carried out, including several mining sector sustainability-focused projects through which we identified relevant sustainable practices and technologies that have been successfully implemented in the mining sector worldwide.

The review involved collecting best practices from European and overseas extractive industries, focusing on advanced technologies and methodologies that have demonstrated significant environmental and economic benefits. This includes practices related to recycling and reprocessing, waste management, renewable energy integration, and the use of digital technologies for sustainability.

A selection of practices and tools applicable to SMEs in the I4-GREEN regions was selected. The selected practices and tools have been evaluated for their feasibility, potential impact on sustainability, and adaptability to SMEs and different operational contexts, ensuring that they can be effectively implemented with available resources and capabilities.

The selected practices and tools will be introduced to SMEs through project and post-project events and workshops, and collaboration with industry experts. The goal is to equip SMEs with the knowledge and resources necessary to adopt these sustainable practices effectively, allowing for further post-project impact.

2. Historical Context and Current Trends in Circular and Sustainable Practices in Mining

Mining plays a vital role in human progress, fueling industrial growth, technological advancements, and economic development worldwide. Historically, mining practices focused on resource extraction to meet increasing global demand, often with limited attention to long-term sustainability. However, as environmental stewardship has expanded, so too has the mining sector's commitment to reducing its impact on ecosystems and local communities while ensuring that resources are used efficiently and responsibly.

In the latter half of the 20th century, growing awareness of environmental issues, such as resource depletion and pollution, prompted the industry to adopt more environmentally conscious practices. The introduction of environmental impact assessments (EIAs) and stricter regulatory frameworks marked a turning point in mining, encouraging companies to evaluate and manage their environmental footprint. This period also saw mining companies embracing a more balanced approach, considering both economic and environmental factors.

The concept of sustainable development, highlighted by the 1987 Brundtland Report, became increasingly influential in shaping mining practices. It called for strategies that meet present needs without compromising future generations' ability to meet their own, aligning with the industry's shift toward more responsible resource management. As a result, mining companies began integrating corporate social responsibility (CSR) initiatives, focusing on minimizing environmental impact while supporting the development of local communities. These efforts paved the way for the industry to move beyond resource extraction toward a model that embraces sustainability as a core value.

In recent decades, the adoption of circular economy principles has transformed the mining sector. Instead of the traditional "take, make, dispose" approach, the circular economy promotes the reuse, recycling, and repurposing of materials to extend their lifecycle and reduce waste. This shift has led to exciting innovations in recycling technologies, waste management, and energy use, positioning the mining industry as a key player in global sustainability efforts.

Recent initiatives such as the European Green Deal and the EU Critical Raw Materials Act exemplify the growing momentum for mining sustainability. The European Green Deal aims to make Europe climate-neutral by 2050, with a focus on reducing carbon emissions, promoting resource efficiency, and fostering a circular economy. Mining plays a key role in this transition by providing critical raw materials for green technologies, such as batteries, electric vehicles, and renewable energy systems. The Raw Materials Act complements this by ensuring secure, sustainable, and responsible access to essential raw materials. These efforts encourage mining companies to adopt greener practices, reduce environmental impact, and align with global sustainability goals. By supporting innovation and sustainable resource management, the mining industry is positioning itself as a crucial player in the shift toward a more circular and resilient economy, contributing not only to economic growth but also to the preservation of the planet for future generations. In Spain, the AENOR certification for sustainable mining and metallurgical management (UNE 22480:2019 and UNE 22470:2019) plays a key role. Many mining companies obtain the certification as a mark of quality in the sustainable management of their operations. It covers economic, social, and environmental indicators (gases, dust, water, soil, discharges, waste, etc.). On the other hand, in 2022, the Roadmap for the Sustainable Management of Mineral Raw Materials, which covers 3 of the 4 I4-GREEN regions, was launched. This roadmap promotes actions related to the use of mining waste dumps and pits, recycling, emissions, digitization, and more.

3. Latest Technology Developments

Circular and sustainable practices in mining refer to processes and technologies that aim to reduce the environmental footprint of mining activities, promote the efficient use of resources, and ensure the long-term viability of mining operations. These practices include recycling waste materials, using renewable energy sources, and minimizing land disruption.

Key trends driving the adoption of circular practices include advancements in technology, increased stakeholder awareness, and stringent environmental regulations. Additionally, economic incentives such as cost savings from waste reduction and resource recovery further promote sustainable mining.

Advanced recycling and reprocessing techniques, innovative waste management strategies, and the integration of renewable energy sources are among the key technologies identified for sustainable mining practices. Sustainable practices offer significant benefits, including reduced environmental impact, cost savings, and enhanced resource efficiency. These practices contribute to the overall sustainability goals of the mining sector.

The I4-GREEN deliverable 6.6 (State of the Art Study on Mine Waste Valorisation Technologies, October 2024) provides an analysis of the technologies used during the waste valorisation process (from exploration to repurposing), including some of the sustainable techniques included in this report.

3.1. Advanced Techniques and Best Practices for sustainability in mining

Recent developments in sustainable mining technology are transforming the industry by integrating advanced tools and methodologies aimed at reducing environmental impact, improving efficiency, and enhancing safety. Specifically, advanced recycling and reprocessing techniques in mining are at the forefront of the industry's push towards sustainability, resource efficiency, and waste minimization. As global demand for metals increases, innovative methods are being developed to not only extract valuable minerals from primary ores but also recover them from tailings and other byproducts of the extraction process. These approaches are critical for addressing environmental concerns and reducing the reliance on traditional mining methods that are sometimes resource-intensive and polluting.

3.1.1. Hydrometallurgy and Bioleaching

Hydrometallurgy and bioleaching represent two leading-edge technologies for metal processing. Hydrometallurgy involves the use of aqueous chemistry to extract metals from ores, concentrates, and recycled or residual materials. It offers a lower environmental impact compared to traditional pyrometallurgical processes (smelting), as it operates at lower temperatures and emits fewer greenhouse gases. Bioleaching and biomining, on the other hand, employ microorganisms to catalyse the breakdown of mineral ores, enabling the extraction of metals such as copper, nickel, cobalt, tungsten and even gold. These methods are particularly useful for processing low-grade ores and waste materials that would otherwise be considered uneconomical or environmentally harmful to mine through conventional methods. These techniques provide a more sustainable alternative to traditional chemical leaching, reducing energy use and environmental contamination. In-situ leaching, or solution mining, is another innovative technique that allows for the extraction of minerals directly from the orebody without physically removing the ore. This method reduces surface disturbance and lowers energy use and waste generation compared to conventional mining techniques.

Figure 1 – Hydrometallurgical installation (left) and bioleaching process (right) (sources: SGS and Acosta Hernández et al. (2023), respectively)

3.1.2. Tailings Management

In parallel with these extraction techniques, modern waste management strategies focus on reducing the amount of waste generated by mining activities. Tailings management has seen significant improvements. In response to high-profile dam failures, companies have moved toward safer methods. Paste backfill techniques allow for the reintegration of mine waste into underground voids, which can stabilize mines and reduce surface waste storage needs. Similarly, dry stacking of tailings, for instance, is gaining traction as a safer and more sustainable alternative to traditional wet tailings storage facilities, which are susceptible to dam failures and environmental contamination. Dry stacking involves dewatering tailings to a thick (almost solid) slurry, reducing the risk of catastrophic failures while also minimizing water usage.

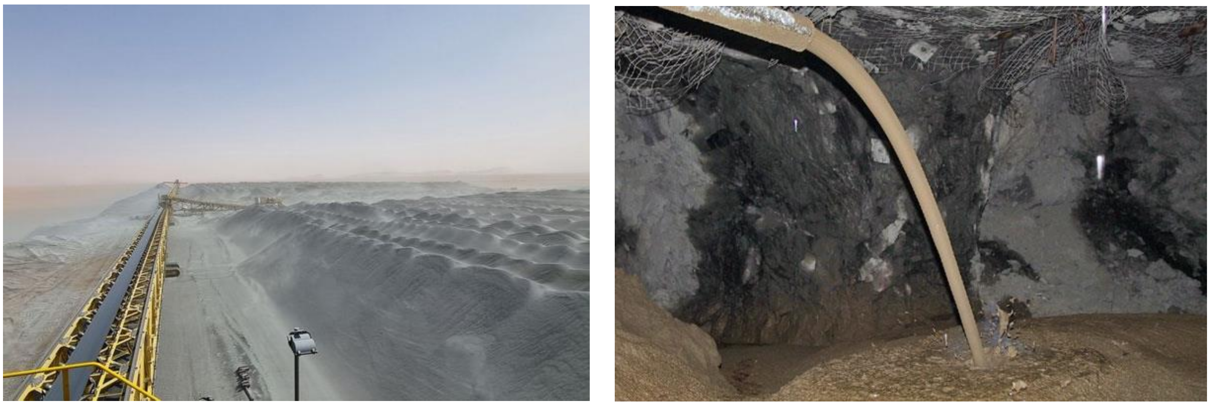

Figure 2 – Tailings dry stacking (left) and paste backfill process (right) (sources: Takraf and Tailings.info, respectively)

Filtration and thickening systems are used to dewater the tailings. In some cases, mechanical and chemical treatments are applied to separate water from solid materials. With these techniques, the removed water can be recycled back into the mining process.

3.1.3. Water management

Water management technologies and techniques are helping mining operations minimize their freshwater consumption. These systems recover nearly all the water used in mining processes, and enable mining operations to reuse water multiple times, minimizing freshwater consumption and reducing the impact on local water resources, which lead to reduced environmental impact. They are of special importance in arid regions where water resources are limited.

Water treatment technologies play a vital role in recycling water and ensuring that it is suitable for reuse in mining operations. Techniques such as reverse osmosis, ultrafiltration, membrane filtration and ecocoagulation (a chemical-free water treatment process that removes suspended solids, heavy metals, and other contaminants.) are common in treating contaminated water from mining processes. These technologies remove dissolved solids, heavy metals, and other contaminants, allowing for cleaner water to be reintroduced into the mining cycle or discharged safely. Furthermore, in regions where freshwater is scarce, particularly in coastal areas, desalination has become an important method for providing water to mining operations. Desalination plants convert seawater into freshwater through processes such as reverse osmosis and other methods like multi-stage flash distillation (MSF) and multi-effect distillation (MED).

Two techniques stand out and are being used with greater frequency to increase mining sustainability:

- Closed-loop water systems are designed to recycle water used during mining operations so that little to no water is discharged into the environment. These systems capture water used in processes such as ore separation, washing, and cooling, and then treat it for reuse. This greatly reduces the need for freshwater intake and minimizes the risk of contaminating surrounding water bodies. The technologies involved range from filtration systems, chemical treatments, reverse osmosis to sedimentation processes.
- Zero-Liquid Discharge (ZLD) is an advanced technique where all water used in the mining process is treated and reused, leaving no liquid waste to be discharged. Any water that cannot be recycled is evaporated, and the remaining solid residues are properly managed. ZLD systems can be particularly beneficial for mining operations in regions where environmental regulations are stringent regarding water discharge or in areas facing severe water shortages. ZLD systems typically use evaporation, crystallization, and reverse osmosis to recover clean water and manage waste solids.

Figure 3 – Zero Liquid Discharge WWTP EPC for the mining complex of Atlantic Copper (Huelva) with a capacity of 1,870 m³/day (source: lantania)

3.1.4. Electrification and Renewable Energy usage

The electrification of mining operations is one of the most impactful trends in reducing carbon emissions in mining operations. Traditional diesel-powered vehicles and machinery are being replaced with electric trucks, loaders, and drills, reducing the reliance on fossil fuels. When powered by renewable energy sources such as solar, wind, or hydropower, these electric machines further help cut emissions and lower operational costs, particularly in remote or off-grid locations.

Incorporating renewable energy such as solar, wind and hydropower into mining operations allows to reduce both operational costs and the industry's carbon footprint. The implementation of battery storage solutions, especially large-scale lithium-ion batteries, also allows mining operations to store excess energy generated during peak production hours for use during times of low energy generation, increasing efficiency and lowering costs. These systems provide reliable power, even in remote locations, helping to smooth out the intermittency of renewable energy sources like wind and solar. These Hybrid energy systems are increasingly being used in remote mining locations where grid connectivity is limited.

Figure 4 – Solar energy installation at Carouse dam (Australia) (source: Northern Star)

3.1.5. Hydrogen Power

Hydrogen-powered equipment is emerging as a sustainable alternative to diesel-fuelled machinery. Hydrogen-powered mining equipment typically uses highly efficient hydrogen fuel cells to generate electricity, which powers the machinery's electric motors. Hydrogen fuel cells convert chemical energy from hydrogen into electricity through an electrochemical process, with water vapor being the only byproduct. This makes the technology zero-emissions at the point of use, meaning there are no carbon emissions from the operation of the equipment itself.

Figure 5 – Anglo American's hydrogen-powered truck (source: Mine NRI Digital, Credit: Waldo Swiegers/Bloomberg via Getty Images)

The hydrogen is stored onboard the mining vehicles in high-pressure tanks and can be refuelled in a process similar to that of traditional diesel equipment, although hydrogen refuelling is much faster compared to battery-electric charging. Hydrogen fuel cells are highly efficient and can provide the large amounts of power needed for heavy-duty mining vehicles, such as haul trucks and loaders, without the need for long charging times. This technology represents a promising step towards reducing the carbon footprint of mining operations.

Hydrogen fuel cells emit only water vapor, making them an excellent alternative to diesel-powered equipment, which emits significant greenhouse gases. This equipment typically offers longer operating times compared to battery-electric alternatives, as refuelling is quicker, and hydrogen tanks provide more energy density compared to batteries. This makes hydrogen an ideal solution for large-scale mining operations where machinery needs to run continuously for extended periods. Along with zero carbon emissions, hydrogen fuel cells produce no harmful pollutants like nitrogen oxides (NOx) or particulate matter, which are common emissions from diesel engines. This improves air quality in and around mining sites, particularly in underground mines where air quality is a critical concern.

3.1.6. Automation and robotics

Automation and robotics are transforming the mining industry by increasing efficiency, improving safety, and reducing the environmental impact of mining operations. Using advanced technologies, such as autonomous vehicles, drones, and remote-controlled machinery, mining companies can optimize resource extraction and streamline operations while reducing costs. These technologies are becoming increasingly prevalent, with autonomous haul trucks and drilling equipment now commonplace in large mining operations. These technologies reduce fuel consumption, enhance safety by removing workers from dangerous environments, and improve operational consistency. Robotics are also being used in hazardous areas to perform remote mining tasks, further mitigating risks to human workers.

Figure 6 – UNEXMiN robot UX-1 in the Reiche Zeche in Germany (source: EOS, Credit: Eckardt Mildner)

3.1.7. Digital technologies

The adoption of digital technologies like the Internet of Things (IoT), artificial intelligence (AI), and blockchain is transforming and optimising the way mining companies manage their operations. AI is playing a critical role in optimizing mine operations by analysing vast datasets to maximize ore recovery and minimize waste. Machine learning algorithms help predict equipment failures, allowing for predictive maintenance that reduces downtime and improves operational efficiency. IoT can be used to monitor equipment and environmental conditions in real-time, allowing for proactive maintenance and reducing downtime. Blockchain technology ensures transparency and traceability in the supply chain, promoting ethical sourcing and compliance with environmental regulations. These technologies not only enhance operational efficiency but also contribute to more sustainable mining practices, addressing the new environmental challenges.

Moreover, Digital twins, which are virtual models of physical mining operations, are being used to simulate real-world conditions. This technology allows mining companies to analyse processes, improve decision-making, and enhance safety measures while reducing environmental impacts through more efficient resource management.

3.1.8. Carbon Capture and Storage

Carbon capture and storage (CCS) technologies are being integrated into mining processes to reduce greenhouse gas emissions. By capturing CO_2 and storing it underground, mining companies aim to offset emissions and move towards carbon-neutral operations. One of the current technologies for carbon dioxide removal is the enhanced weathering of waste rocks, especially silicates. In this process, CO2 is removed from the atmosphere and converted to carbonates/bicarbonates.

3.1.9. Control of Mining Gas and Dust Emissions

In mining, harmful gas emissions such as nitrogen oxides (NOx), sulphur dioxide (SO_2), carbon dioxide (CO_2), ammonia (NH_3) volatile organic compounds (VOCs), and particulate matter (PM) pose significant environmental and health risks. Several technologies are available to capture and mitigate these emissions, such as electrostatic precipitators, flue gas desulfurization, selective catalytic and non-catalytic reduction, low-NOx burners, ammonia scrubbing, activated carbon adsorption, biofilters and biotrickling filters, thermal oxidation

On the other hand, adding water mixed with specific dust-binding agents to roads and transport routes can help reduce the spread of dust. This includes eco-friendly polymers and chemical surfactants that reduce airborne particles without affecting the soil's health. Additionally, mist spraying and surface wetting are key to control dust particles. Other dust collection systems are Baghouse Filters (industrial dust collectors with baghouse filtration capture dust particles from airflows in crushing and screening processes), and Cyclone Separators (used to separate dust particles from air streams by creating a vortex, allowing larger dust particles to be collected and removed).

4. Additional practices

Additionally, other practices are applied to better characterise the mining process and its impact, and thus reduce this impact and pinpoint additional measures for sustainability. The most applied techniques are Life Cycle Assessments (LCA), Social License to Operate (SLO), modern characterization of historical tailings, modern valorisation of mining waste, custom designs for the involved processes, modern security measures, rehabilitation and biodiversity conservation.

Finally, community engagement and social responsibility are crucial to complete the sustainability efforts. As an example of community engagement and social responsibility, the I4-GREEN project tackles these issues through the quadruple helix, with direct involvement and support of the Governments of Extremadura, Castilla y León, and Andalusia the participation of RTOs, 2 industrial clusters, associations and two SME driven industrial pilots in direct liaison to relevant industries that tractorise the impact on the region to valorise the investment and transform it into direct benefit for the society, in terms of economy prosperity, recovery and employment.

4.1. Case Studies

4.1.1. The I4-GREEN Pilots

The Iron Holm Oak (IHO) Pilot is an industrial mining initiative centred around the recovery of endogenous resources, including key EU strategic raw materials like rare earth elements (REEs), from iron ore processing tailings. It integrates cutting-edge technologies while adhering to high standards of environmental, social, and economic sustainability. The project's sustainable approach is reinforced through water recycling, the use of green energy, automation, sustainable operations, mobility solutions, circular recovery, digitization, and community engagement. The companies chosen through the I4-GREEN Open Call to collaborate on the IHO project will provide their expertise to further drive IHO sustainability in:

- Life Cycle Assessment, which evaluates environmental risks, energy usage, and carbon emissions.
- Water Resource Analysis to assess water use and management.
- Tailings Characterization, focusing on the composition of historical tailings and the projected impact of future tailings from the processing plant.
- Waste Valorisation, aiming to extract rare earth elements (REEs) from iron ore tailings via gravimetric methods, improving both the environmental footprint and the circular economy within mining.
- Optimization of Mining Operations for greater efficiency.
- Revision of Basic Engineering and the Techno-Economic Assessment for the processing plant, covering equipment and process flow diagrams.

In parallel, the E-LIX Pilot introduces an innovative hydrometallurgical technique for leaching copper and zinc sulphides (chalcopyrite and sphalerite). The E-LIX System is based on a novel electrochemical process that extracts valuable metals from sulphide concentrates using a unique catalyst under specific physicochemical conditions. The system is currently being implemented on an industrial scale at the E-LIX Phase I Plant and is expected to unlock significant polymetallic resources in Atalaya's Riotinto District, including strategic EU materials like copper, cobalt, platinum group metals (PGMs), and zinc, by improving recovery rates from low-grade ores.

Support for the E-LIX project's sustainability, provided through the I4-GREEN Open Call, includes:

- Design and installation of a water management system.
- Environmental Assessment, which calculates the carbon and water footprint of the project and assesses its impact on other mineral processing technologies.
- Solid-liquid separation systems using pressurized membrane filtration for zero effluent discharge, ensuring continuous operation within a closed circuit.
- Custom design for sedimentation and clarification systems, particularly concerning piping, instrumentation, and fluid transport solutions.
- Fire safety enhancement, focusing on advanced fire detection, prevention, and extinguishing systems for the E-LIX plant.

4.1.2. Overseas and European Case Studies

Case studies from various international, national and regional mining companies highlight successful implementations of advanced technologies (Table 1) and demonstrate the industry's commitment to sustainability. The references at the end of this document provide the specific documents through which the information has been gathered and serves for further consult.

These sustainable practices have resulted in reduced environmental footprints, lower operational costs, and enhanced community relations. The adoption of renewable energy and water recycling technologies has particularly contributed to significant cost savings and compliance with environmental regulations.

Table 1. Overseas and European case studies

Mine	Country/Region	Measures	Outcome
Rio Tinto	Global	Carbon Capture and Storage technologies (involvement in the Hilt CCU project to develop economically viable CCS solutions)	Lower carbon emissions
Olympic Dam	Australia	Water Recycling and Management: Desalination plant for fresh water supply and recycling of process water	Reduction of water consumption
Carouse Dam	Australia	Energy efficiency: installation of solar panels	Diminished reliance on diesel generators, reduced carbon footprint
BHP	Australia	Automated and Remote-Controlled Equipment: automated haul trucks and drilling systems	Safety enhancement, reduction of fuel consumption, and overall increase of operational efficiency
Rio Tinto	Australia	Autonomous Haulage Systems (AHS): autonomous haul trucks equipped with GPS, radar, and artificial intelligence	Increased human safety, lower fuel consumption and emissions.
Fortescue Metals Group	Australia	Biodiversity conservation: implementation of programs focused on habitat restoration and monitoring of wildlife populations	Minimization of land disturbance. Recovery of local/regional biodiversity
Gorgon CO_2 Injection Project	Australia	Carbon Capture and Storage (monitored by the Department of Mines Industry Regulation and Safety - DMIRS)	Reduction of atmospheric CO_2
Goldcorp (now part of Newmont)	Canada	Precision mining: advanced sensors and data analytics	Optimisation of the mining process: waste reduction and improved efficiency of resource use
Diavik Diamond Mine	Canada	Water management system: water recycling, treatment facilities, and monitoring programs	Minimisation of water usage and prevention of contamination
Mount Polley	Canada	Tailings Management: Dry stack tailings	Reduction of tailings dam failures and of water usage
Ranglan Mine	Canada	Energy efficiency: Installation of wind turbines	Diminished reliance on diesel generators, reduced carbon footprint
El Teniente	Chile	Underground efficient mining technology: use of block caving mining method	Reduction of surface disturbance and waste generation
		Tailings management: Implementation of a thickening process to reduce water content.	Reduction of water usage and of the risk of dam failures
		Renewable Energy: Implementation of hydroelectric plants and energy-efficient equipment and practices	Minimization of energy consumption and reduction of carbon footprint
		Community Engagement programs: including job creation, local business support, and infrastructure development	Social and economic benefits. Social acceptance.
Escondida	Chile	Water Management: Desalination plant for fresh water supply and recycling of process water	Reduction of freshwater consumption
Kevitsa	Finland	Energy efficiency: Variable-speed drives and high-efficiency motors for the energy-intensive crushing and grinding activities	Reduction of energy consumption
		Water management: system for recycling and treating process water	Minimisation of freshwater consumption. Accomplishment of environmental standards for discharged water.

Table 1. Overseas and European case studies

Mine	Country/Region	Measures	Outcome
		Biodiversity and rehabilitation action plan.	Protection of local flora and fauna. Restoration of natural habitats.
B2Gold Fekola	Mali	Renewable Energy: Application of a solar-battery hybrid system	Reduction of fuel consumption and consequent carbon emissions
Oyu Tolgoi	Mongolia	Renewable energy: Wind, solar and hydropower combination	Reduction of carbon footprint
Panasqueira	Portugal	Energy efficiency: energy-saving technologies and solar-battery hybrid systems	Reduced carbon footprint
		Environmental Management Systems	Sustainable use of resources and minimisation of environmental impacts
		Waste Management: Tailing reprocessing - Bioleaching	Sustainable use of resources and minimisation of environmental impacts
		Community engagement: job creation, education opportunities, health and safety	Social acceptance increased
Aljustrel	Portugal	Energy efficiency: energy-saving technologies and solar-battery hybrid systems	Reduced carbon footprint
		Environmental Management Systems	Sustainable use of resources and minimisation of environmental impacts
		Community engagement: job creation, education opportunities, health and safety	Social acceptance increased.
Neves-Corvo	Portugal	Energy efficiency: energy-saving technologies and renewable energy sources.	Reduced carbon footprint
		Waste Management: Tailing reprocessing	Waste optimisation
		Water Management: Zero-Liquid Discharge, Filtration technologies	Diminished environmental impact of used water
		Community engagement: job creation and education opportunities	Social acceptance increased
Riotinto	Spain	Renewable Energy: construction of a photovoltaic solar plant	Reduction of GHG emissions
		Water management & recycling	Reduced freshwater usage
		Investment in research and technologies for increased sustainability	Reduced environmental footprint

Table 1. Overseas and European case studies

Mine	Country/Region	Measures	Outcome
		Investment in local communities, procurement from local suppliers, support to social initiatives	Social acceptance increased
Cobre Las Cruces	Spain	Hydrometallurgical processing	Reduced carbon footprint
		Water recycling	Reduced water consumption
		Tailings management: Dry-stack	Improved safety and environmental outcomes,
		Renewable Energy Integration: solar farm and battery storage system	Reduced carbon footprint
		Rehabilitation of nearby ecosystems	Biodiversity restoration
Artesiaga	Spain	Rehabilitation of nearby ecosystems	Biodiversity restoration
		Control of gas emissions (NOx, SOx)	Lower environmental impact
Aitik	Sweden	Energy efficiency: electric vehicles and machinery, powered by renewable energy sources such as hydroelectric power	Lower carbon emissions
		Water management: closed-loop water recycling system	Reduction of freshwater consumption
		Digital technologies: Real-time data monitoring and automated systems	Increased operation efficiency. Minimization of waste and environmental disturbance

5. Analysis and Recommendations

The mining industry, traditionally associated with significant environmental impacts, has been making notable progress toward adopting more sustainable practices. This shift is driven by global concerns over climate change, resource depletion, and the growing demand for ethically sourced raw materials. Although sustainability is an important trend in Europe and worldwide, countries like Australia and Canada have emerged as global leaders in the adoption of sustainable practices in the extractive industries, setting benchmarks for environmental responsibility and social accountability. These countries have developed and implemented best practices that can serve as models for extractive industries worldwide, particularly those operating overseas. In Europe, regions like Andalusia, Extremadura, Castilla y León in Spain, and Alentejo in Portugal, which are home to significant mining operations, are central to this sustainable transition. These areas are increasingly aligning their mining activities with environmental and social responsibility, offering a roadmap for the future of sustainable mining.

The industry has made considerable strides in reducing carbon emissions, integrating renewable energy, improving water management, and adopting circular economy principles. For example, mining companies have begun to electrify their operations by deploying electric and hydrogen-powered mining equipment. In regions with a strong mining presence, the use of hydrogen-powered vehicles and renewable energy sources like solar and wind is critical. Companies like Anglo American and Rio Tinto have already set benchmarks by incorporating hydrogen technology and renewable energy systems into their mines, which can serve as models for the Iberian Peninsula.

In terms of water management, which is crucial in dry regions, mining companies have adopted advanced recycling systems like closed-loop water systems and ZLD technologies. These systems ensure that water used in the mining process is treated and reused, reducing freshwater consumption and minimizing the environmental impact on local water resources. Water recycling technologies are particularly relevant in water-scarce regions, where the strain on water resources can pose a significant challenge. By adopting waterless or low-water processing technologies, these regions can further reduce their dependency on local water supplies, ensuring that both mining and agriculture can coexist sustainably.

Another area of significant progress is waste management and the adoption of circular economy principles. The reprocessing of tailings to recover valuable minerals is becoming more widespread, reducing waste while extracting additional materials such as copper and rare earth elements. In the I4-GREEN regions, where mineral resources are abundant, reprocessing tailings can help reduce environmental liabilities while contributing to resource efficiency.

Automation and robotics are playing a vital role in improving the sustainability of mining operations in Europe. In regions like Andalusia, where the Las Cruces copper mine operates, the use of autonomous vehicles, drones, and remote-controlled machinery is helping to optimize resource extraction, reduce energy consumption, and enhance worker safety. AI and machine learning are also being applied to predict equipment failures, optimize resource extraction, and improve energy efficiency, which is particularly relevant for operations in the technologically advanced mines of southern Spain. The shift toward automation not only improves operational efficiency but also aligns with the broader sustainability goals of the European Green Deal, which aims to make Europe carbon-neutral by 2050. The use of digital twins—virtual replicas of mining operations—can help optimize processes in real-time, reducing waste and improving the efficiency of resource extraction in Spain and Portugal's key mining regions. These digital tools allow companies to simulate entire operations, from resource extraction to processing, helping identify areas for improvement and making data-driven decisions that enhance sustainability.

Beyond technological advancements, community engagement and ethical sourcing are critical elements of sustainable mining. In the I4-GREEN mining regions, mining companies must work closely with local communities to ensure that the benefits of mining activities are shared. This includes creating jobs, investing in local infrastructure, and supporting education and healthcare. As an example, in Canada partnerships with indigenous communities have become a standard practice, ensuring that mining operations respect the rights and traditions of local populations. This collaboration extends to shared decision-making, training, and employment opportunities for indigenous people, fostering economic development and reducing conflict. Overseas operations can adopt similar practices by prioritizing meaningful consultation and community integration, ensuring that local populations benefit from mining activities in a fair and transparent manner. Ethical sourcing of minerals is also vital, and the use of blockchain technology to ensure the traceability of materials can help guarantee that minerals are extracted responsibly and in compliance with international environmental and social standards.

Post-mining practices, such as rehabilitation of mined land and biodiversity restoration are also integral to sustainable mining. In regions like Castilla y León, where open-pit mining has left scars on the landscape, companies must prioritize land rehabilitation efforts to restore ecosystems and make the land usable for other purposes. Early planning for mine closure and the use of nature-based solutions, such as reforestation and wetland restoration, will be key to ensuring that the environmental impact of mining in Europe is minimized, and that local biodiversity is preserved.

Through continued innovation, mining can not only reduce its environmental footprint but also support Europe's broader transition to a green economy, ensuring that the industry remains viable, competitive, and aligned with global sustainability goals.

6. Conclusions

Adopting circular and sustainable practices in mining is essential for reducing environmental impacts and ensuring the long-term viability of the industry. The mining industry is making significant strides, but further progress is needed to address challenges related to carbon emissions, water usage, and waste management.

To strengthen sustainability in mining, particularly in Europe's critical mining regions, companies should develop clear sustainability goals and accelerate the adoption of clean energy solutions like hydrogen and electrification, invest in advanced water recycling systems, and continue to reprocess mining waste to recover valuable resources. Continued support and training for SMEs are essential to ensure the successful adoption of sustainable practices. This includes technical assistance, access to funding, and ongoing mentorship. Furthermore, encouraging collaboration and networking between SMEs and other stakeholders in the mining industry will facilitate knowledge sharing and innovation. This has been a key activity during the I4-GREEN project.

On their side, policymakers must strive to provide incentives (such as tax benefits, grants, and regulatory support) to drive SMEs' adoption of sustainable practices, and development of research and innovation. Policies should encourage the development of circular economy frameworks and promote international cooperation.

Finally, collaborating with local governments and communities to ensure fair and equitable resource distribution will also be essential to achieving long-term sustainability. With the right investments in technology, infrastructure, and community engagement, regions like the ones involved in the I4-GREEN project (Andalusia, Extremadura, Castilla y León, and Alentejo) through real case studies like IHO and E-LIX, can lead the way in demonstrating how mining can transition to a more sustainable and responsible future.

7. Resources

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