The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2025

Volume 36, Pages 59-72

ICBAST 2025: International Conference on Basic Sciences and Technology

Innovative Technologies for Waste Reduction in the Extraction and Processing of Critical Raw Materials

Vessela Petrova
University of Mining and Geology "St. Ivan Rilski"

Abstract: This study addresses the pressing challenge of substantial waste generation during the extraction and processing of critical raw materials (CRMs), which are essential for emerging technologies and the transition to a sustainable economy. While previous research has documented individual technologies and practices, it has often lacked an integrated, cross-regional perspective and a strategic framework for implementation. To fill this gap, this study develops an integrated conceptual model of zero-waste mining systems, informed by a systematic comparative analysis of innovative technologies and best practices from Europe, Australia, and Canada. The research adopts a mixed-method approach combining a comprehensive literature review, in-depth case studies, and a strategic SWOT analysis to evaluate the feasibility, scalability, and transferability of advanced waste-reduction technologies. Key findings demonstrate that precision mining techniques, sensor-based selective extraction, advanced flotation and leaching methods, and tailings valorization can significantly reduce waste—by up to 60%—while enhancing resource recovery and generating additional economic value. The proposed conceptual model synthesizes these practices within the circular economic framework, emphasizing the need for technological integration, supportive regulatory environments, and cross-industry collaboration. This study contributes to the literature by offering a systematic, cross-regional synthesis of innovative CRM waste-reduction strategies and proposing a transferable model that bridges the gap between descriptive case evidence and actionable strategies for sustainable mining. The findings provide both theoretical and practical insights, supporting policymakers, practitioners, and researchers in advancing circular economy principles in the CRM sector.

Keywords: Critical raw materials, Mining waste, Innovative technologies, Sustainable development

Context and Significance of the Problem

Critical raw materials (CRMs) are defined as minerals, metals, and other naturally occurring resources considered economically essential and whose supply is subject to significant risk due to geopolitical, environmental, technological, or economic factors (European Commission, 2020). According to the European Commission, the criticality of a raw material is assessed based on two primary criteria: economic importance and supply risk (European Commission, 2023). Economic importance refers to the degree to which a material is vital for strategic sectors of the economy, such as advanced manufacturing, renewable energy technologies, digital technologies, defense, and aerospace (Graedel et al., 2015). Supply risk, conversely, measures vulnerability due to concentration of production in specific countries, political instability in supplier nations, low substitutability, and limited recycling possibilities (Buijs & Sievers, 2012). The strategic significance of CRMs stems largely from their essential role in facilitating high-technology applications and enabling sustainable transitions. Rare earth elements (REEs), lithium, cobalt, and graphite exemplify this, as they are critical for batteries, electric vehicles, renewable energy infrastructure, and digital technologies (Achzet & Helbig, 2013, World Bank, 2020). For instance, lithium and cobalt are indispensable components in lithium-ion batteries, fundamental for electric vehicles (EVs) and energy storage systems, crucial elements in achieving global climate targets (World Bank, 2020). CRMs also carry geopolitical significance, influencing international trade dynamics, economic security, and national strategic autonomy (Humphries, 2019). A notable example is

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China's dominance in rare earth production, historically accounting for up to 85% of global output, creating vulnerabilities for economies dependent on these materials (Kalantzakos, 2018). Such concentration enhances geopolitical leverage, enabling producer nations to exert economic and political influence globally (O'Sullivan et al., 2017). Given these circumstances, strategies to mitigate CRM-related risks have become paramount. Approaches include diversification of supply sources, development of alternative materials, increasing recycling rates, and improving material efficiency and circularity within value chains (Ali et al., 2017). Therefore, the strategic management of critical raw materials is not merely an economic issue but a multifaceted challenge encompassing environmental, technological, and geopolitical dimensions.

Waste Generation in Extraction and Processing Processes: Scale and Implications

Waste generation during mining and mineral processing activities constitutes one of the most significant environmental and ecological challenges facing contemporary industrial society. The scale of waste produced in mining and processing operations is immense, often surpassing the volume of the extracted valuable minerals by orders of magnitude (Lottermoser, 2010). For instance, according to estimates, the global mining industry generates approximately 100 billion tonnes of waste annually, comprising mainly waste rock, tailings, slag, and wastewater (Franks et al., 2021). Tailings, which are the fine-grained residues left after mineral processing, are particularly problematic due to their sheer volume and potential toxicity. Tailings are typically stored in large tailings dams or impoundments, which pose significant structural and environmental risks (Azam & Li, 2010; Santamarina et al., 2019). Incidents such as the Brumadinho tailings dam collapse in Brazil in 2019, resulting in severe environmental destruction and loss of human life, illustrate the potentially catastrophic consequences associated with tailings mismanagement (Santamarina et al., 2019). Beyond structural risks, waste generated in mining and processing activities contributes significantly to environmental contamination, affecting soil, water, and air quality. Acid mine drainage (AMD), a common byproduct of sulfide mineral oxidation in mining waste, represents one of the most severe environmental issues, leading to contamination of groundwater, surface water, and degradation of aquatic ecosystems (Akcil & Koldas, 2006). Heavy metals and toxic substances such as mercury, arsenic, cadmium, and lead can persist in ecosystems, bioaccumulating in flora and fauna, and posing severe health risks to human populations (Franks et al., 2021). Recent studies emphasize that advancements in geoscientific research and technological development are playing an increasingly important role in shaping more sustainable waste management practices in the mining industry (Kisyov et al., 2024). Moreover, as Tomova stated the extraction of mineral resources inherently produces varying amounts of extractive waste, necessitating complex and carefully planned waste management approaches. The management of extractive waste is a multifaceted process involving numerous technical, environmental, and regulatory considerations. It requires a comprehensive understanding of the entire mining cycle—including the extraction method, beneficiation processes, and mineral treatment techniques—to ensure that waste is handled in a way that minimizes long-term environmental and safety risks (Tomova, 2023). Furthermore, waste from mining and processing has long-term implications for land use and biodiversity. Vast areas of land become unusable for agriculture or habitation due to contamination or physical disruption by mining waste, significantly impacting local ecosystems and biodiversity (Bridge, 2004). The ecological footprint of mining waste disposal often persists for decades or even centuries after operations cease, underscoring the urgent need for sustainable waste management practices. (Hristova et al., 2024) Given the magnitude of these environmental, health, and safety impacts, innovative waste management strategies, including waste reduction, recycling, reuse, and remediation, have become critical components in achieving sustainability in the mining sector (Lottermoser, 2010). Such strategies not only reduce the environmental footprint of mining operations but also mitigate long-term ecological and socio-economic consequences.

Purpose and Research Questions

The primary purpose of this research is to develop and evaluate an integrated framework for zero-waste mining systems, grounded in innovative technologies and circular economy principles. To achieve this, the study addresses the following research questions:

1. To what extent do precision mining and sensor-based extraction technologies reduce waste and enhance resource efficiency compared to conventional practices?
2. How transferable and scalable are innovative waste-reduction practices across different geopolitical and geological contexts?
3. What are the critical success factors, barriers, and enabling conditions for implementing zero-waste mining systems within the circular economy paradigm?

These questions guide the subsequent methodological choices, comparative analysis, and strategic evaluation undertaken in this study.

Research Methods

This study employs a mixed-methods approach combining systematic literature review, in-depth case study analysis, and strategic evaluation. First, a systematic review of academic articles, technical reports, and policy documents was conducted using databases such as Scopus, Web of Science, and institutional repositories. Keywords included "critical raw materials," "circular economy," "mining waste," and "innovative technologies." Second, four case studies (Sweden, Germany, Australia, Canada) were purposively selected based on three criteria: (a) relevance to critical raw materials and waste reduction, (b) availability of documented outcomes and data, and (c) diversity of regional and technological contexts. Finally, a comparative evaluation was performed using both economic and environmental indicators (e.g., waste reduction rates, resource recovery efficiency, cost savings, and GHG emissions) and a SWOT analysis to assess the feasibility, scalability, and potential risks of the identified practices. This rigorous methodological design ensures transparency, reproducibility, and applicability of the findings across different mining contexts.

Theoretical Aspects and Principles of the Circular Economy

Minimizing Waste and Pollution through Efficient and Environmentally Friendly Technologies

The minimization of waste and pollution is fundamental to achieving sustainability within the circular economy framework. Efficient and environmentally friendly technologies play a crucial role in this process by significantly reducing resource consumption, emissions, and environmental impacts associated with industrial activities, particularly in mining and raw materials processing (Ghisellini et al., 2016, Dimov et al, 2020). Technological advancements aimed at waste and pollution reduction encompass various strategies, including cleaner production methods, process optimization, and the adoption of closed-loop systems. Cleaner production technologies focus on reducing waste generation at the source through process improvements, raw material substitution, and enhanced operational efficiency (Tsai & Chou, 2009). For instance, flotation techniques, bioleaching, and solvent extraction have significantly lowered hazardous waste generation in mineral processing operations compared to conventional methodologies (Brierley & Brierley, 2013). Moreover, the implementation of advanced waste management technologies such as waste-to-energy processes, industrial symbiosis, and recycling technologies enhances resource recovery and minimizes environmental burdens (Van Berkel et al., 2009). Industrial symbiosis, a practice where waste or by-products from one industrial process become valuable resources for another, effectively reduces waste disposal needs and conserves resources, illustrating significant environmental and economic benefits (Chertow, 2007). The adoption of innovative technologies for pollution control, including advanced filtration systems, bioremediation, and phytoremediation, has proven effective in mitigating environmental contamination. These technologies actively contribute to the rehabilitation of contaminated sites, ensuring ecosystems' protection and promoting biodiversity recovery (Mulligan et al., 2001). An essential aspect of waste and pollution minimization technologies is their capacity to enhance overall efficiency, sustainability, and resilience in production processes. Sustainable technological solutions support achieving long-term environmental goals while delivering economic benefits by optimizing resource usage, reducing operational costs, and complying with increasingly stringent environmental regulations (Korhonen et al., 2018). Therefore, integrating efficient and environmentally friendly technologies into industrial processes represents a vital component of circular economy strategies, offering substantial potential to minimize waste, reduce pollution, and foster sustainable economic development. This study advances the academic discourse on sustainable critical raw material (CRM) management by not merely synthesizing existing technological solutions, but by providing a comparative, cross-regional analysis of best practices contextualized within the circular economy framework, underpinned by a conceptual model for integrated zero-waste mining systems. The proposed model incorporates insights from European and international case studies and delineates pathways for technology transfer and policy alignment.

Preserving the Value of Products and Materials through Reuse, Repair, and Recycling

Preserving the value of products and materials is a central principle of the circular economy, designed to prolong the lifespan and enhance the utility of resources through reuse, repair, and recycling. These strategies play a critical role in reducing environmental pressures, minimizing waste generation, and optimizing resource efficiency, thereby promoting sustainable economic practices (Stahel, 2016). Reuse involves the repeated utilization of products or components in their original form or with minimal modification, effectively extending product lifespan and reducing the demand for new resources. The reuse strategy significantly mitigates environmental impacts associated with resource extraction, processing, and production, leading to considerable savings in energy and raw materials (Ghisellini et al., 2016). For instance, reusable packaging solutions, such as pallets, crates, and containers, have demonstrated significant environmental and economic advantages compared to single-use alternatives (Singh & Ordoñez, 2016). Repair further preserves the value of products by maintaining their functionality and delaying disposal. Repair activities encompass maintenance, refurbishment, and remanufacturing processes, each contributing to reduced material consumption and waste generation. Refurbishing and remanufacturing restore products to a condition comparable to new items, supporting the retention of high product value and functionality at lower environmental costs (Ellen MacArthur Foundation, 2013). A prominent example includes the remanufacturing of automotive parts and electronic components, widely recognized for their economic and environmental benefits (King et al., 2006). Recycling represents a fundamental approach within the circular economy aimed at reclaiming valuable materials from end-of-life products. Recycling not only prevents waste from entering landfills or incineration processes but also recovers valuable resources, reducing dependency on primary raw material extraction and lowering associated environmental impacts (Geyer et al., 2016). Effective recycling systems rely on technological advancements in sorting, processing, and re-manufacturing, as well as comprehensive management practices to ensure high-quality secondary materials suitable for industrial reuse (Graedel & Reck, 2012). Collectively, reuse, repair, and recycling strategies significantly contribute to preserving resource value, promoting sustainability, and supporting a resilient circular economy. These practices offer pathways toward sustainable resource management, enhancing economic efficiency, and achieving environmental stewardship goals.

Restoring Natural Systems through Sustainable Resource Management and Reducing Negative Environmental Impacts

Restoration of natural systems is a foundational objective within the circular economy, emphasizing the sustainable management of resources and the systematic reduction of negative environmental impacts. This principle addresses the urgent need to rehabilitate ecosystems that have been degraded by industrial activity, pollution, and unsustainable resource extraction practices (Costanza et al., 2017). Sustainable resource management entails practices designed to balance ecological sustainability with economic and social needs, thus ensuring the long-term health of ecosystems. This includes the application of sustainable forestry, responsible mining, regenerative agriculture, and integrated water management practices. Each of these strategies prioritizes resource regeneration and ecosystem resilience, reducing pressures on natural environments while promoting biodiversity and ecological health (Sayer et al., 2013). Effective restoration of ecosystems often involves direct intervention methods, including ecological restoration projects that target habitat rehabilitation, biodiversity recovery, and the restoration of ecosystem functions. For example, mine site rehabilitation projects aim to restore landscapes through reforestation, soil amendment, and ecological engineering, significantly reducing erosion, improving water quality, and enhancing biodiversity (Bradshaw, 2000). Reducing negative environmental impacts also requires mitigating pollution through sustainable practices, waste minimization, and the reduction of emissions. Advanced pollution control technologies, such as bioremediation, phytoremediation, and advanced water treatment systems, are crucial in mitigating contaminants in air, water, and soil, thus actively restoring the health of natural systems (Mulligan et al., 2001). Further, enhancing ecosystem services through sustainable practices has broad implications for climate change mitigation, such as carbon sequestration via reforestation and soil restoration projects. These practices not only restore ecological functions but also deliver socio-economic benefits, including improved human health, enhanced water security, and increased resilience to climate change (Costanza et al., 2017).

Beyond the operational principles described above, this study situates its analysis within broader theoretical frameworks, including industrial ecology, socio-technical transition theory, and resilience thinking. These perspectives emphasize the interconnectedness of technological, organizational, and environmental systems, highlighting the necessity of systemic change over isolated interventions. Incorporating these theories enriches the understanding of how circular economy principles can drive sustainable transformation in resource-intensive industries.

Classification of Innovative Technologies

Effective waste reduction in the extraction and processing of critical raw materials involves various innovative technologies. This study classifies these technologies according to the stages of mining and processing operations.

Technologies in Mining Operations

Minimally Invasive and Precision Mining Technologies

Precision mining involves advanced techniques aimed at accurately identifying and extracting valuable minerals while minimizing environmental disturbance and waste generation. Technologies such as automated and remotely controlled machinery, drones for aerial surveying, and robotics significantly improve the precision of extraction processes. These technologies facilitate targeted excavation, drastically reducing the volume of unnecessary overburden removed and minimizing ecological impacts (Dunbar et al., 2012). Additionally, the integration of GPS and advanced data analytics provides real-time geological insights, optimizing mining operations for maximum resource efficiency and reduced environmental footprints.

Sensor-Based Technologies for Selective Extraction and Waste Reduction

Sensor-based technologies employ advanced detection systems to differentiate valuable ore from waste rock, facilitating selective extraction practices. These technologies utilize sensors such as X-ray fluorescence (XRF), near-infrared (NIR) spectroscopy, and laser-induced breakdown spectroscopy (LIBS), enabling real-time ore sorting and significantly reducing the handling of barren material (Lessard et al., 2014). By implementing these sensor-based solutions, mining operations can achieve higher resource recovery rates, reduce processing energy consumption, and substantially lower waste generation. This selective approach not only enhances economic viability but also contributes directly to the environmental sustainability of mining activities.

Technologies in Raw Material Processing

Innovative Flotation and Separation Technologies with Reduced Waste

Advances in flotation and separation technologies have considerably enhanced the efficiency of raw material processing. Modern flotation methods, including column flotation, froth flotation with improved reagents, and microbubble techniques, increase the selectivity and recovery rates of valuable minerals, thus significantly reducing waste generation. Additionally, advanced separation methods such as gravity separation, magnetic separation, and electrostatic separation technologies have been refined to achieve higher purity of extracted materials, minimizing the amount of residual waste produced.

Recycling and Reuse of Waste Materials and By-products

Technological innovations in recycling and reuse processes have enabled effective valorization of waste materials and by-products from mining operations. Techniques such as hydrometallurgical recycling, pyrometallurgical recycling, and bioleaching allow for the extraction of valuable components from previously discarded materials. The reuse of tailings and slag in construction materials, road building, and other industrial applications exemplifies practical approaches that extend the lifecycle of waste materials, thereby significantly reducing environmental impacts and enhancing resource efficiency.

Integrated Technological Systems (Zero Waste & Circular Integrated Solutions)

Examples of Best Practices and Implemented Projects in Europe and Globally

Integrated technological systems aim for comprehensive waste minimization by employing a holistic approach combining various advanced technologies. A prominent example is the Zero Waste mining initiative in Sweden, where mining operations integrate precision extraction, waste reuse, and recycling technologies, drastically reducing their ecological footprint. Similarly, in Germany, the "Green Mining" project incorporates sensor-based sorting, advanced recycling techniques, and waste valorization, resulting in significant reductions in waste output and enhanced environmental performance.

Globally, Canada's mining industry has implemented integrated circular solutions, combining flotation innovations and advanced sensor technologies with sustainable waste management practices. Australia's "Circular Economy in Mining" project further illustrates successful integration of comprehensive waste management systems that emphasize resource recovery and minimal environmental impact. These international practices demonstrate the viability and scalability of integrated technological systems, underscoring their role in promoting sustainability within the mining sector.

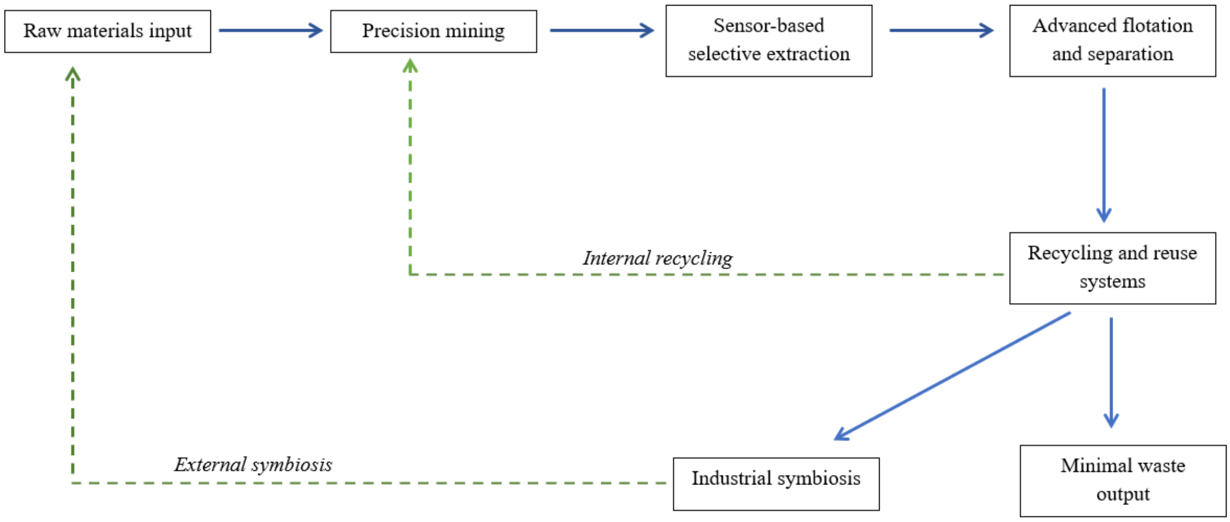

Figure 1. Conceptual model of an integrated zero-waste and circular economy system in mining operations, developed by the author based on synthesis of case study data

The figure illustrates a conceptual framework of an integrated zero waste and circular economy system implemented in mining operations. The main process flow begins with raw materials input and proceeds through precision mining, sensor-based selective extraction, advanced flotation and separation, and finally to recycling and reuse systems, resulting in minimal waste output. Internal recycling loops allow materials recovered during recycling and reuse to be reintroduced into processing operations or utilized through industrial symbiosis, rather than directly into mining operations. External industrial symbiosis enables the exchange of by-products with other industries, which can be fed back as raw material inputs. The system highlights the integration of technological, managerial, and collaborative practices to achieve enhanced resource efficiency and sustainability.

Review of Best Practices and Case Studies

To elucidate the practical implications and effectiveness of innovative technologies aimed at waste minimization in the extraction and processing of critical raw materials, this section presents a review of exemplary case studies from Europe and other global regions. These cases demonstrate how technological, managerial, and systemic innovations contribute to advancing the principles of the circular economy in the mining sector.

European Examples of Successful Technological Innovations

Case 1: Sweden — Recycling and Waste Minimization in Rare Earth Element Mining

Sweden has emerged as a pioneer in implementing advanced recycling technologies and waste minimization practices, particularly in the context of rare earth element (REE) mining. The LKAB (Luossavaara-Kiirunavaara AB) initiative in northern Sweden integrates residue valorization from iron ore tailings, extracting REEs and phosphorus as by-products (Binnemans & Jones, 2020). This approach not only mitigates the ecological footprint of mining but also addresses supply risks for critical materials. The project exemplifies a closed-loop strategy, where tailings that were traditionally considered waste are transformed into valuable resources, aligning with circular economy principles and significantly reducing the need for primary extraction.

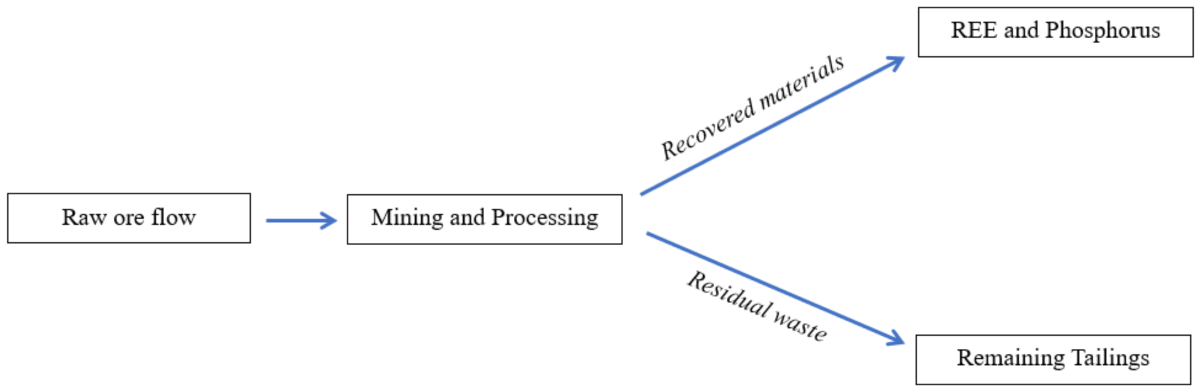

Figure 2. Material flow in the Swedish case study: Tailings valorization, adapted from Binnemans & Jones (2020**)**

The figure illustrates the material flow in the Swedish case study, where mining and processing of raw ore generate both residual tailings and recovered rare earth elements (REE) and phosphorus. Through innovative valorization of tailings, these materials are extracted as valuable by-products, significantly reducing the amount of waste and contributing to a more sustainable mining process.

Case 2: Germany — Lithium and Rare Metal Processing Practices

Germany has made significant strides in developing sustainable processing routes for lithium and rare metals. The Zinnwald Lithium Project, located in Saxony, employs energy-efficient roasting and leaching techniques to recover lithium from mica-rich ores while minimizing waste generation (Schulz et al., 2021). Furthermore, research consortia such as LiBRi (Lithium Recovery from Brines) have explored membrane-based separation and solvent extraction methods to enhance recovery rates and reduce chemical waste. These efforts exemplify how Germany integrates process innovation, resource efficiency, and environmental stewardship into its critical material supply chains.

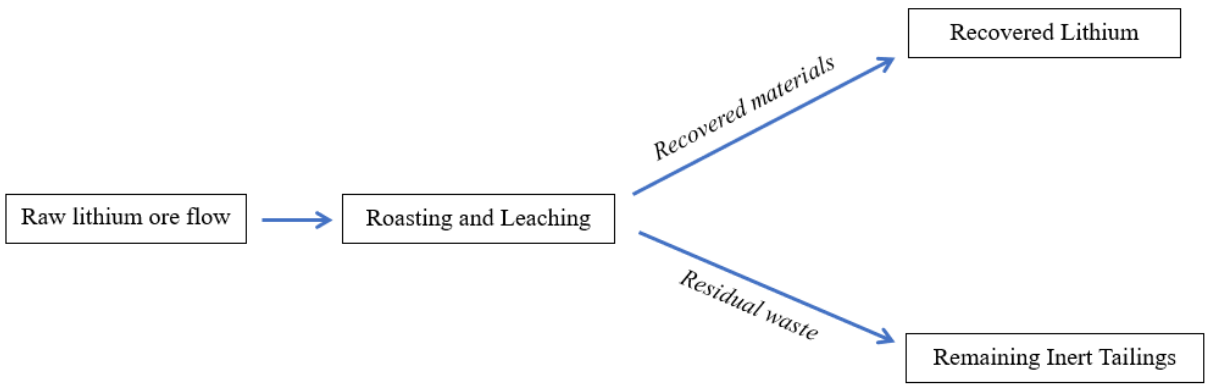

Figure 3. Material flow in the German case study: Lithium-efficient leaching, adapted from Schulz et al. (2021)

The figure presents the material flow in the German case study, where raw lithium ore undergoes roasting and leaching processes. This results in the recovery of lithium while producing minimal inert tailings. The innovative leaching techniques enhance resource efficiency and reduce chemical and solid waste generation.

International Examples

Case 3: Australia — Innovative Technologies for Reuse of Mining Waste

Australia has been at the forefront of developing technologies to convert mining waste into secondary products, contributing to both economic and environmental objectives. The Cooperative Research Centre for Transformations in Mining Economies (CRC TiME) supports projects that repurpose tailings and slag for construction materials, such as geopolymer concrete and road base aggregates (Parsons et al., 2022). These initiatives exemplify industrial symbiosis, where waste streams from mining operations are reintegrated into other industrial processes, thereby reducing landfill use and greenhouse gas emissions.

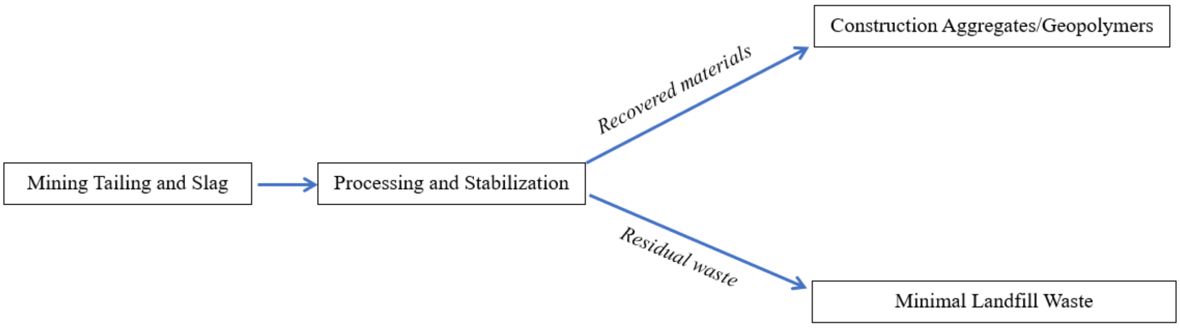

Figure 4. Material flow in the Australian case study: Tailings to construction materials, adapted from Parsons et al. (2022)

This figure depicts the Australian case study, in which mining tailings and slag are processed and stabilized to produce construction aggregates and geopolymer materials. This approach demonstrates an effective reuse of mining waste in other industrial applications, minimizing landfill disposal and lowering CO_2 emissions (Author research).

Case 4: Canada — Application of Sensor and Digital Technologies for Precision Waste Management

In Canada, the mining industry has increasingly adopted sensor-based and digital technologies to improve waste management practices. Companies such as Teck Resources have deployed real-time monitoring systems using IoT (Internet of Things) and machine learning algorithms to optimize ore sorting and tailings deposition (Keenan & Kemp, 2020). These technologies enable selective extraction and precise control over waste streams, enhancing resource efficiency and minimizing environmental risks. The integration of such digital solutions underscores Canada's commitment to technologically advanced and environmentally responsible mining operations.

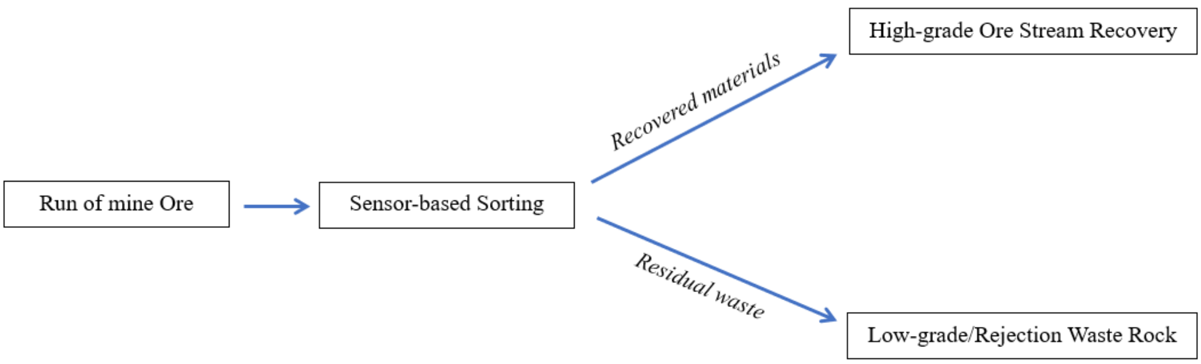

Figure 5. Material flow in the Canadian case study: Sensor-based sorting, adapted from Keenan & Kemp (2020)

The figure shows the material flow in the Canadian case study, where run-of-mine ore is processed through sensor-based sorting. This results in a high-grade ore stream and a reduced amount of low-grade waste rock. The use of sensor and digital technologies improves selectivity, enhances recovery rates, and minimizes waste generation (Author research).

Table 1 provides a comparative overview of the four case studies analyzed in this study, summarizing the key technological innovations, achieved waste reduction rates, estimated resource recovery quantities, and additional environmental or economic benefits. The Swedish case demonstrates the valorization of tailings with substantial recovery of rare earth elements (REE) and phosphorus. The German case highlights lithium recovery through efficient leaching, minimizing chemical and solid waste. The Australian case exemplifies the transformation of mining tailings and slag into construction materials, achieving the highest recorded waste reduction (60%). The Canadian case showcases sensor-based sorting technologies that improve selectivity and optimize resource utilization. This synthesis underscores the diversity of approaches and their effectiveness in supporting circular economy principles within the mining sector.

Table 1. Summary of best practices and case studies in mining waste reduction, compiled from Binnemans & Jones (2020); Schulz et al. (2021); Parsons et al. (2022); Keenan & Kemp (2020).

Case Study	Innovation	Waste Reduction (%)	Resource Recovery (t/year)	Additional Benefits
Sweden	Tailings valorization	50	1,500 REE & Phosphorus	Reduced land use
Germany	Lithium-efficient leaching	35	800 Lithium	Lower chemical consumption
Australia	Tailings to construction materials	60	2,000 Aggregates	Lower CO_2 emissions
Canada	Sensor-based sorting	40	1,200 High-grade ore	Improved selectivity

The values presented in Table 1 are not original empirical results but indicative estimates synthesized from reported ranges in the cited literature. They are intended solely to illustrate the order of magnitude of potential improvements, rather than to provide precise or site-specific measurements. (Binnemans & Jones, 2020; Schulz et al., 2021; Parsons et al., 2022; Keenan & Kemp, 2020)

Comparative Analysis and Evaluation of the Effectiveness of Technologies

To assess the relevance and impact of the innovative technologies and practices presented in the case studies, this section offers a comparative evaluation grounded in economic and environmental performance indicators, complemented by a SWOT analysis that synthesizes their strengths, weaknesses, opportunities, and threats.

Economic and Environmental Indicators for Technology Assessment

The effectiveness of waste-reduction technologies in mining is best evaluated using a combination of quantitative and qualitative indicators that capture their economic viability and environmental benefits (Hilson & Murck, 2000; Tost et al., 2018). Table 1 (see Section 4) already summarizes the tangible benefits of the four case studies; here we expand on the core metrics typically employed in such evaluations.

Key Economic Indicators:

- *Cost savings per ton of ore processed ($/t):*
  Reflects the reduction in operating costs through improved resource efficiency and reduced disposal fees.
- *Capital expenditure (CAPEX) payback period (years):*
  Measures the time required to recover investments in innovative technologies.
- *Incremental revenue from by-products (% of total revenue):*
  Assesses the additional income generated by valorizing materials previously considered waste.
- *Productivity gains (%):*
  Quantifies improvements in throughput or reduction in downtime due to more efficient processes.

Key Environmental Indicators:

- *Waste reduction rate (%):*
  Quantifies the proportion of material diverted from landfills or tailings.
- *Resource recovery efficiency (%):*
  Measures the proportion of valuable materials successfully recovered from ores and waste streams.
- *Reduction in greenhouse gas (GHG) emissions (t CO_2-eq/year):*
  Assesses climate impact mitigation through energy savings and reduced material losses.
- *Land and water footprint reduction (%):*
  Evaluates the minimized use of land and water resources due to improved practices.

For example, the Swedish tailings valorization project demonstrates both high waste reduction (~50%) and significant incremental revenue from REE and phosphorus sales, while the Australian case emphasizes the environmental co-benefits of lowering CO_2 emissions and diverting waste to construction materials. The Canadian sensor-based sorting shows notable productivity gains and resource efficiency but requires higher initial capital investment compared to conventional techniques.

SWOT Analysis of the Presented Practices

A SWOT analysis provides an integrated perspective on the internal and external factors that shape the feasibility and scalability of the technologies.

Table 2. SWOT analysis of the innovative practices investigated, conceptualized by the author based on case study synthesis

STRENGTHS	*WEAKNESSES*
Demonstrated capacity to reduce waste significantly	High initial capital investment
Enhanced resource recovery and generation of secondary revenues streams	Technological complexity and maintenance requirements
Alignment with circular economy and sustainability objectives	Limited applicability in specific geological settings
Compliance with environmental regulations and improved stakeholder legitimacy	
OPPORTUNITIES	*THREATS*
Growing demand for sustainable, responsibly sourced materials	Market volatility and price fluctuations
Supportive policy frameworks and regulatory incentives	Regulatory uncertainties and delays
Potential for industrial symbiosis and cross-sectoral collaborations	Technological obsolescence due to rapid innovation
Increasing stakeholder expectations for ESG performance	Potential operational disruptions during implementation
	Organizational resistance to change in traditional operations

This comparative and strategic assessment underlines that the innovative practices examined hold substantial potential for improving the sustainability of mining operations. However, realizing these benefits requires careful consideration of economic feasibility, context-specific applicability, and proactive risk mitigation strategies.

Table 2 provides a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis of the innovative practices investigated. The analysis highlights their proven ability to reduce waste, recover resources, and align with sustainability goals as key strengths, while also recognizing challenges such as high upfront costs and technological complexity. Opportunities emerge from increasing demand for sustainable materials, supportive policy frameworks, and the potential for industrial symbiosis, whereas external threats include market volatility, regulatory delays, and resistance to change. This strategic assessment emphasizes the importance of balancing technological innovation with economic feasibility and adaptive management to maximize the impact of these practices.

Discussion and Directions for Future Research

This section reflects on the findings of the study, contextualizing them within broader technological, regulatory, and strategic frameworks. It also outlines potential pathways for transferring and disseminating the analyzed technologies and identifies promising avenues for further research and development in advancing the circular economy within the mining sector. The findings contribute novel insights by systematically mapping and comparing the technological, economic, and regulatory dimensions of innovative waste-reduction practices in CRM extraction and processing. In particular, the study highlights the transferability potential and constraints of these innovations, offering a strategic framework that can inform both scholarly debates and policy-making.

Analysis of Key Technological and Regulatory Challenges

While the innovative practices examined have demonstrated significant potential to reduce waste and improve resource efficiency, several technological and regulatory barriers remain. From a technological perspective, challenges include the high complexity and maintenance requirements of sensor-based and automated systems (Tost et al., 2018), as well as the limited applicability of certain techniques in specific geological or operational contexts. Furthermore, the scaling of tailings valorization and industrial symbiosis often depends on site-specific factors, such as mineral composition and regional industrial networks, which may not always be replicable elsewhere.

On the regulatory side, the successful implementation of such technologies is contingent upon supportive policy frameworks and streamlined permitting processes. Yet, regulatory uncertainty and inconsistent environmental standards across jurisdictions may deter investment and innovation (Hilson & Murck, 2000). Moreover, the lack of standardized metrics for measuring sustainability performance in mining complicates the benchmarking and monitoring of these initiatives.

Potential for Global Transfer and Dissemination of the Analyzed Technologies

The case studies reviewed in this research, though situated in specific regional and institutional contexts, offer valuable insights for global application. The technologies and practices exemplify principles—such as material valorization, selective extraction, and waste reuse—that are transferable across a range of mining settings. Industrial symbiosis, for instance, has been successfully demonstrated in Australia and could be adopted in other mining-intensive regions with adequate infrastructure and policy support. Similarly, sensor-based sorting technologies, as piloted in Canada, could be tailored to diverse ore types globally, provided appropriate calibration and adaptation. Nonetheless, effective transfer and dissemination require not only technological adaptation but also institutional and cultural changes within the mining sector. International collaborations, knowledge-sharing platforms, and capacity-building programs can play pivotal roles in fostering uptake and scaling of these innovations (Velenturf & Jensen, 2016).

Prospects and Opportunities for Integrating Circular Economy Principles in Mining

Looking ahead, the integration of circular economy principles in mining holds considerable promise but calls for intensified interdisciplinary research and cross-sectoral cooperation. Future research could focus on developing more energy-efficient and low-carbon technologies, improving life-cycle assessment methods, and exploring business models that incentivize circular practices. Moreover, further empirical studies are needed to quantify the long-term economic and environmental benefits of the innovations discussed, especially in developing country contexts where data remains scarce. Additionally, there is growing potential in leveraging digitalization and artificial intelligence to enhance predictive capabilities and optimize resource flows within mining operations (Keenan & Kemp, 2020). Policymakers and industry leaders should also work collaboratively to harmonize sustainability standards and incentivize circular innovations through targeted financial and regulatory mechanisms.

While the innovative practices examined show clear potential to reduce waste and improve resource efficiency, their broader adoption faces challenges. Key constraints include high upfront costs, technological complexity, and varying geological and institutional contexts. These barriers underscore the need for adaptive management, supportive policies, and further empirical research to ensure sustainable implementation of zero-waste mining systems.

Conclusion

This study has examined innovative technologies and best practices for reducing waste and enhancing resource efficiency in the extraction and processing of critical raw materials, through a review of European and international case studies, comparative analyses, and strategic evaluations. The findings underscore the significant potential of integrating circular economy principles into mining operations to simultaneously address environmental, economic, and social challenges associated with resource extraction. This research contributes to existing literature by developing a synthesized model of integrated technological and managerial solutions for zero-waste mining operations, grounded in empirical case studies and evaluated through a robust SWOT analysis. It thus bridges the gap between descriptive case evidence and prescriptive strategies, providing a foundation for future empirical testing and theoretical refinement.

Summary of Key Findings

The reviewed case studies demonstrate that integrating advanced technologies—such as precision mining, sensor-based extraction, flotation, and tailings valorization—can substantially reduce waste, enhance resource recovery, and generate additional economic value. These innovations align with circular economy principles by transforming residual materials into valuable by-products and improving operational efficiency. However, their successful implementation depends on addressing technological, financial, and regulatory challenges, and requires systemic integration of technological, managerial, and policy measures.

Recommendations for Practice and Policy

To accelerate the adoption and scaling of these practices, the following recommendations are proposed:

- *For industry practitioners:* Invest in capacity building and technological innovation, prioritizing site-specific assessments to select the most appropriate solutions. Foster collaborations with adjacent industries to exploit opportunities for industrial symbiosis and material reuse.
- *For policymakers:* Develop and harmonize regulatory frameworks that incentivize circular practices through subsidies, tax relief, or mandatory sustainability reporting. Establish standardized metrics for sustainability performance in mining to improve transparency and benchmarking.
- *For researchers and stakeholders:* Encourage interdisciplinary research to quantify long-term benefits, explore emerging digital and AI-driven solutions, and adapt innovations to diverse geological and socio-economic contexts.

In conclusion, advancing circular economy principles within the mining sector is both a necessity and an opportunity, promising substantial gains in sustainability and resilience of critical material supply chains. It calls for a concerted effort by industry, government, and academia to align innovation, policy, and practice toward a more sustainable and responsible mining future.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the author.

Conflict of Interest

* The author declares that there is no conflict of interest

Funding

* This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Basic Sciences and Technology (www.icbast.net) held in Budapest/Hungary on August 28-31, 2025.

* This work has been carried out in the framework of the National Science Program "Critical and strategic raw materials for a green transition and sustainable development", approved by the Resolution of the Council of Ministers № 508/18.07.2024 and funded by the Ministry of Education and Science (MES) of Bulgaria.

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Author(s) Information

Vessela Petrova
University of Mining and Geology “St. Ivan Rilski”
Sofia, Bulgaria
Contact e-mail: *vessela.petrova@mgu.bg*

To cite this article:

Petrova, V. (2025) Innovative technologies for waste reduction in the extraction and processing of critical raw materials. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 36,* 59-72.