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Opinion

Critical Minerals Recovery Beyond the Mine: System-Level Challenges for the Next Decade

Priscilla P. Nelson*

Colorado School of Mines, Golden, Colorado, USA

***Corresponding author:** Priscilla P. Nelson, Colorado School of Mines, Golden, Colorado, USA

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Abstract

Global demand for critical minerals is increasing rapidly as economies transition toward electrification, renewable energy systems, advanced electronics, and digital infrastructure. Policy responses to this demand have largely emphasized exploration and development of new primary deposits. While new mines will remain essential, a substantial portion of the metals required for modern technologies already resides in materials that have been mined but not fully utilized, including tailings, waste rock, metallurgical residues, and process water streams. These materials represent a vast and largely underdeveloped secondary resource base.

Recovering critical minerals from these materials is not simply a matter of applying conventional extraction technologies. Rather, it requires rethinking the mining system as an integrated resource conversion platform capable of transforming low-grade and heterogeneous materials into reliable supply. This article identifies four system-level challenges that must be addressed for secondary recovery to contribute meaningfully to global critical mineral supply. These challenges include [1] making secondary resources investable through rigorous characterization and uncertainty quantification, [2] redesigning mineral processing systems to capture byproducts that historically reported to tailings, [3] developing technologies capable of recovering metals from dilute water streams and ultra-low-grade materials, and [4] scaling recovery through modular and distributed processing systems capable of operating beyond traditional large centralized plants.

Addressing these challenges will require coordinated advances across geoscience, mineral processing, chemical engineering, water treatment, and systems engineering. The transition from a linear extraction model toward an integrated resource recovery framework represents one of the most important transformations facing the mining industry in the coming decades.

Keywords: Critical Minerals; Mine Waste Recovery; Tailings Reprocessing; Resource Circularity; Mineral Processing Innovation; Secondary Resources; Mine Water Recovery; Distributed Processing Systems

Abbreviations: TSF: Tailings Storage Facility; REE: Rare Earth Elements; MLA: Mineral Liberation Analyzer; QEMSCAN: Quantitative Evaluation of Minerals by Scanning Electron Microscopy; AMD: Acid Mine Drainage

Introduction

Critical minerals have become central to discussions of global economic security and technological development. Metals such as lithium, cobalt, rare earth elements, gallium, germanium, and others play essential roles in energy storage systems, high-performance magnets, electronics, aerospace systems, and advanced manufacturing technologies. Rapid growth in demand for these materials has exposed vulnerabilities in global supply chains, prompting governments to prioritize domestic production and diversified sourcing.

Most policy discussions focus on accelerating the discovery and development of new mines. Exploration incentives, permitting reform, and strategic stockpiles are increasingly common policy instruments intended to address supply risks. While these initiatives are important, they address only one dimension of the broader resource challenge.

A second dimension lies in the enormous quantities of material already extracted by the mining industry. Over the past century, mining and mineral processing operations have generated billions of tonnes of tailings and waste rock. Historically, these materials were viewed as unavoidable byproducts of extracting a limited set of target metals. Advances in analytical technology and evolving market conditions have revealed that many of these materials contain significant quantities of critical elements that were not previously recovered.

These secondary materials represent an opportunity to expand the effective resource base without the environmental and logistical challenges associated with new mine development. However, the transition from waste storage to resource recovery is far from straightforward. Secondary materials are often heterogeneous, poorly documented, and physically complex. Recovering value from them requires advances not only in extraction technology but also in characterization, systems integration, and economic evaluation.

This article proposes that progress in critical minerals recovery will depend on addressing four fundamental challenges that extend across the mining value chain. These challenges are not isolated technological problems but rather system-level transformations affecting how mining operations are designed, monitored, and integrated with downstream supply chains.

Discussion

Making Secondary Resources Investable

The Resource Definition Problem

The first barrier to large-scale recovery from mine waste lies in the absence of reliable resource definition. Conventional ore deposits are evaluated through systematic drilling, sampling, and modeling programs that allow mineral resources to be classified with quantified uncertainty. In contrast, many legacy tailings facilities were constructed during periods when such documentation was not required.

Records describing the mineralogical composition, particle size distribution, and geochemical variability of tailings deposits may be incomplete or entirely absent. In many cases, tailings were deposited over decades under varying operational conditions, resulting in complex stratigraphic layering and heterogeneous mineral distributions. Without reliable knowledge of these characteristics, potential recovery projects face substantial uncertainty. Investors and regulators require credible estimates of both resource magnitude and process recoverability before committing to new recovery initiatives.

Geometallurgical Characterization of Secondary Deposits

Addressing this challenge requires the development of systematic geometallurgical characterization frameworks specifically designed for secondary resources. These frameworks should integrate multiple analytical approaches, including automated mineralogy, geochemical analysis, particle size distribution measurement, and physical property testing. Advanced analytical tools such as QEMSCAN and MLA now allow detailed identification of mineral phases and their associations within complex materials. When combined with geostatistical modeling, these techniques can support the development of three-dimensional resource models for tailings deposits similar to those used for primary ore bodies.

Imaging and Mapping Legacy Deposits

Geophysical imaging technologies offer an additional avenue for understanding the internal structure of large tailings facilities. Techniques such as seismic tomography and electrical resistivity imaging can reveal variations in density, saturation, and layering within deposits. These insights are valuable not only for resource characterization but also for stability assessments and environmental monitoring.

The integration of geophysical data with geochemical and mineralogical analysis could enable the creation of digital models of tailings facilities that simultaneously support resource recovery planning and risk management.

Redesigning Mineral Processing for Byproduct Capture

Historical Focus on Primary Metals

Traditional mineral processing systems were optimized to recover a limited number of primary metals from ore bodies. Elements present in minor concentrations were frequently ignored or discarded because their recovery did not justify additional processing costs. However, many of these elements have since become strategically important. Rare earth elements, cobalt, gallium, germanium, and other materials often occur in trace quantities within primary ore minerals or associated gangue phases. As a result, they frequently report to tailings during processing.

Deportment Analysis

Understanding how these elements behave during processing is a critical step toward improved recovery. Deportment analysis examines the distribution of elements across mineral phases and process streams. By identifying where critical elements are lost within processing circuits, engineers can redesign flowsheets to capture these materials before they report to waste streams.

Adaptive Processing Systems

Advances in sensing technologies and automated mineralogical analysis may enable real-time monitoring of mineral associations within processing streams. Such capabilities could support adaptive process control strategies that adjust separation parameters dynamically in response to changes in ore composition.

Incorporating these capabilities into mineral processing

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systems could transform critical mineral recovery from an afterthought into an integrated component of plant design.

Recovering Metals from Water and Ultra-Low-Grade Streams

Water Circuits as Resource Streams

Water plays a central role in mineral processing operations. Process water circuits transport particles, facilitate chemical reactions, and enable separation processes. Over time, these water systems accumulate dissolved metals released during grinding and flotation operations.

Mine-impacted waters associated with tailings facilities and waste rock deposits may also contain elevated concentrations of dissolved metals. Historically, water treatment systems focused on removing these metals to meet environmental discharge standards.

Emerging Recovery Technologies

Recent advances in separation chemistry suggest that some of these metals could be recovered economically. Technologies such as selective sorbents, ion exchange systems, and electrochemical recovery methods can target specific elements at low concentrations.

If integrated effectively with existing water treatment systems, these approaches could transform water management infrastructure into resource recovery platforms.

Scaling Recovery Through Modular and Distributed Systems

Limits of the Centralized Processing Model

Most mineral processing systems rely on large centralized facilities designed to process high volumes of ore from a single mine. This model works well for large deposits but is poorly suited to smaller or geographically dispersed secondary resources.

Modular Processing Concepts

Modular processing systems offer a potential solution. Containerized processing units capable of performing specific separation steps could be deployed at multiple locations. These systems would reduce infrastructure requirements and allow recovery technologies to operate at smaller scales.

Distributed Recovery Networks

Distributed processing systems may also enable regional recovery networks in which multiple waste streams feed centralized or semi-centralized processing hubs. Such networks could significantly expand the range of materials that can contribute to critical mineral supply.

Conclusion

Critical minerals recovery from mine wastes, tailings, and water systems represents one of the most promising opportunities for expanding global mineral supply while reducing environmental impacts associated with new mine development. However, realizing this opportunity requires a shift from a linear extraction model toward a more integrated resource recovery framework.

The challenges outlined in this article-resource characterization, process redesign, low-grade recovery technologies, and distributed processing systems-highlight the interdisciplinary nature of this transformation. Progress will require collaboration among geoscientists, metallurgists, chemical engineers, and systems engineers. If these challenges can be addressed successfully, the mining industry may enter a new phase in which materials previously considered waste become an important component of the global critical minerals supply system.

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Conflict of Interest

The author declares no conflict of interest.

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