INFORMATICS JOURNALS

Feature Article JC3M

Critical Minerals Metals and Materials

eISSN: xxxx-xxxx; DOI: 10.18311/c3m/2026/56304

Volume 1, Issue 2, June 2026, pp. 115-120

Understanding Minerals and Waste/Gangue Association and Separation Chemistry for Different Ores is the Core Knowledge in the Critical Minerals Sector

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This is the exact reason why the "Great Mineral Mismatch" exists in today's supply chains. The primary bottleneck in the global energy transition is rarely a lack of raw ore in the ground—it is the sheer chemical and metallurgical complexity of economically separating target elements from gangue at scale. If mining is simply the logistics of moving materials, the chemical separation is where the actual value is unlocked and where the technological moats are built.

Here is how that separation chemistry defines the operational reality for key critical minerals:

1. Lithium and the DLE Revolution

Historically, lithium extraction relied on energy-intensive roasting of hard rock (spodumene) or the agonizingly slow solar evaporation of salar brines.

Today, the industry is pivoting toward **Direct Lithium Extraction (DLE)**, which is entirely a chemical separation challenge. DLE bypasses evaporation by using highly selective chemistries to pull lithium directly out of brines while leaving heavily concentrated gangue elements—primarily magnesium and calcium—behind. This is achieved through advanced sorbents, ion-exchange resins, or solvent extraction. If the chemistry isn't perfectly dialed into the specific elemental profile of that exact brine, the resins foul, and the entire processing plant becomes economically unviable.

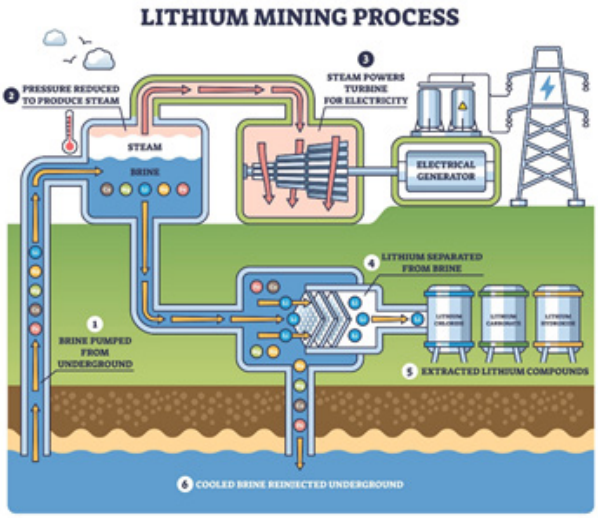


Figure 1. Lithium extraction from underground brine.

Source: VectorMine/Getty Images.

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2. Rare Earth Elements (REEs): The Ultimate Bottleneck

Separating REEs from gangue—and more importantly, from each other—is arguably the most difficult chemical processing challenge in the mining sector.

Because the 15 lanthanides have nearly identical atomic radii and share the same +3 oxidation state, they behave almost identically in chemical reactions. Once separated from radioactive gangue like thorium or uranium, separating adjacent REEs (e.g., Neodymium from Praseodymium) requires hundreds of sequential solvent extraction stages. The operational discipline required to manage the massive volumes of hazardous acids and solvents in these plants is immense.

3. Copper and Cobalt: Manipulating Surface Chemistry

For base-but-critical metals like copper and cobalt, the core technology is **froth flotation**, which relies entirely on manipulating the surface chemistry of the crushed ore.

The goal is to make the valuable sulfide minerals hydrophobic (water-repelling) and the silica-based gangue hydrophilic (water-attracting).

- **Collectors** (like xanthates) are added to the slurry, chemically binding only to the target metal sulfides.
- **Frothers** are added to stabilize air bubbles pumped into the tanks.
- The hydrophobic copper/cobalt particles attach to the bubbles and float to the surface for collection, while the gangue sinks to the tailings.

A slight miscalculation in the pH of the slurry or the dosage of the collector reagents means millions of dollars of critical metals are accidentally sent to the tailings dam.

Understanding these chemical pathways isn't just a metallurgical requirement; it dictates the geopolitical map of where processing facilities are built, how environmental clearances are managed, and how vulnerable a mineral's supply chain truly is.

How to begin with a critical mineral ore when this knowledge is absent. What are the first logical steps?

When encountering a newly discovered critical mineral ore where separation chemistry and waste/gangue association are entirely unknown, attempting early-stage extraction or chemical leaching is a common but expensive error. The presence of target elements in an assay does not guarantee they can be economically separated. **To bridge the gap between geology and metallurgy, the mining industry relies on a foundational discipline known as process mineralogy**—the practical study of an ore's physical and chemical properties specifically to guide the design and optimization of metallurgical flowsheets[1]. The initial evaluation follows a strict, data-driven hierarchy to eliminate processing blind spots:

1. Representative Sampling and Geometallurgical Mapping

Before any laboratory equipment is used, the orebody must be sampled to account for its natural variability. An orebody is never uniform; its mineralogy shifts continuously with depth, weathering profiles, and geological faults.

The deposit is mapped into geometallurgical units—distinct zones of ore that share similar compositional and textural properties. This allows engineers to predict that samples from a specific unit will behave similarly during processing[1]. Testing blended whole-ore samples too early obscures these critical variations and frequently leads to a flowsheet that fails under real-world plant conditions.

2. High-Definition Automated Mineralogy

Once representative samples are secured, they are subjected to comprehensive characterization using Automated Scanning Electron Microscopy (ASEM) systems. Technologies like QEMSCAN (Quantitative Evaluation of Mineralogy by Scanning Electron Microscopy) and Mineral Liberation Analyzers (MLA) utilize backscattered electrons and X-ray spectra to generate rapid, digital mineral maps of the ore[2].

This step definitively identifies the host minerals. A target metal like cobalt might be hosted in an easily recoverable sulfide, or it could be locked in a highly refractory silicate gangue that renders chemical separation economically unviable. Modern ASEM systems are particularly crucial for critical minerals, as they simultaneously map bulk gangue and detect micron-sized trace minerals that could serve as highly valuable by-products or deleterious contaminants[2].

3. Grain Size and Liberation Analysis

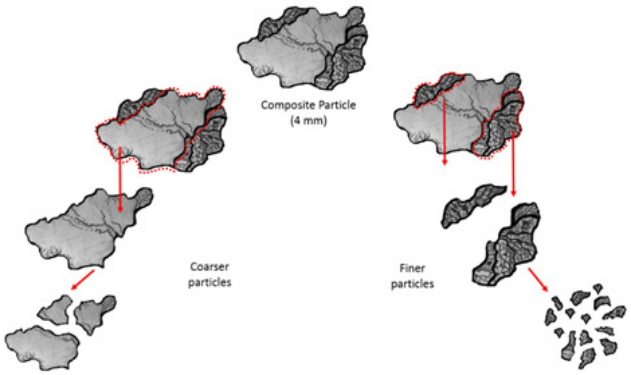


Figure 2. Mineral liberation during crushing using grade-by-size analysis.

Knowing the minerals is only the first step; understanding how they physically bind to the waste rock dictates the processing economics. The automated mineralogy data is leveraged to determine the liberation size—the exact particle size to which the ore must be crushed and ground so that the valuable mineral physically detaches from the gangue. If a critical mineral is exceptionally fine-grained and locked tightly inside a hard quartz matrix, the energy required for comminution (grinding) might exceed the economic value of the metal. Identifying these locking mechanisms early provides the critical data needed to decide whether to pursue physical separation (like froth flotation) or alternative bulk routes like whole-ore leaching[1].

4. Bench-Scale Metallurgical Testing

Only after the mineralogy, grain size, and liberation properties are thoroughly modeled does actual separation testing begin. This stage starts at the bench scale (using kilograms of ore) rather than the pilot scale.

Armed with predictive mineralogical data, multidisciplinary teams of geologists and process engineers can confidently select the most logical physical and chemical unit operations—such as gravity concentration, magnetic separation, or initial acid baking—to begin developing a preliminary flowsheet[1].

How to make the first move to build capacity and capability

To make the first move in building institutional capacity for critical minerals, research centers and metallurgical institutes must shift away from the traditional, siloed approach where geologists log core samples and metallurgists independently run chemical tests. Modern extraction—especially for highly complex, fine-grained critical minerals—requires a heavily integrated framework to first decode the chemical associations and then engineer the separation flowsheets[3].

As national frameworks like the National Critical Mineral Mission (NCMM) push for strategic mineral provisioning and the development of specialized Mineral Processing Parks, institutions must align their capital expenditures and R&D strategies with these specific developmental phases.

Phase 1: Capitalizing on Advanced Geometallurgy Infrastructure

The absolute first step for an institution is establishing a world-class process mineralogy laboratory. You cannot separate what you cannot see or quantify.

- **Automated Mineralogy (AM):** Institutions must invest in AM platforms (such as QEMSCAN, MLA, or modern AI-driven equivalents) that utilize scanning electron microscopy to generate quantitative, digital maps of ore samples. This

provides hard data on mineral composition, grain size, and liberation characteristics.

- **3D Non-Destructive Imaging:** Because critical and trace metals are often sub-millimeter in size and locked in complex gangue, modern centers are integrating X-ray Computed Tomography (XCT) with traditional 2D automated mineralogy. This combination allows researchers to visualize the spatial distribution and locking mechanisms of target metals in 3D before the ore is even crushed[4].
- **Geometallurgical Mapping:** By linking this high-resolution mineralogical data with spatial geological models, institutions can predict how different blocks of an orebody will behave during chemical processing, significantly derisking the project economics[3].

Phase 2: Building Bench-to-Pilot Separation Capability

Once the mineral associations are mapped, the institution must build scalable physical and chemical separation capabilities.

- **Modular Bench-Scale Units:** Instead of investing immediately in massive pilot plants, centers should build highly modular bench-scale circuits. This includes flotation cells, magnetic separators, and hydrometallurgical leaching reactors where pH, temperature, and reagent dosages can be tightly controlled.
- **Safety and Chemical Discipline:** Scaling up chemical separation—particularly hydrometallurgy and solvent extraction—introduces massive volumes of hazardous reagents, from reactive oxidizers to corrosive acids. As institutions design these labs, establishing rigorous industrial safety protocols and standard operating frameworks (such as 5S) is a prerequisite to operating safely and securing environmental clearances.
- **Circular Economy Integration:** Modern metallurgical centers must not focus solely on primary ore. Infrastructure must be designed to test the recovery of critical metals from secondary sources, such as mine tailings, waste rock, or end-of-life batteries, aligning with sustainable and circular resource management[5].

Strategic Steps for the "First Move"

To fund and utilize this infrastructure effectively, institutions should operate on a collaborative "hub and spoke" model. The research center acts as the high-tech hub (housing the capital-intensive XCT and AM equipment), partnering with spoke entities like junior exploration companies, manufacturing startups, and local universities. This ensures the expensive infrastructure is constantly utilized by industry partners who supply the raw samples, engineering talent, and real-world separation challenges to solve.

A Special Additional note on Grain Size and Liberation Analysis

Successful beneficiation of these ores requires an intricate understanding of their fundamental physical properties, with grain size distribution and mineral liberation being the most crucial parameters[6].

The Role of Grain Size Analysis

Grain size analysis is the foundational step in determining the comminution (crushing and grinding) strategy for an ore body. Comminution is notoriously the most energy-intensive stage of mineral processing, and striking the balance between over-grinding and under-grinding is vital for economic viability[7].

If critical mineral ores are underground, the valuable minerals remain attached to gangue (waste) minerals, making downstream separation techniques like froth flotation or magnetic separation ineffective. Conversely, over-grinding consumes excessive energy and creates ultra-fine particles known as "slimes." Slimes severely reduce the recovery rates of critical minerals because they coat larger particles and alter the fluid dynamics of processing circuits[8]. Establishing the optimum grind size ensures that the ore is reduced just enough to free the valuable mineral without generating detrimental fines.

Mineral Liberation Analysis

While grain size dictates the physical dimensions of the crushed ore, mineral liberation refers specifically to the percentage of the valuable mineral that occurs as isolated, "free" particles relative to "locked" or composite particles[9]. A particle must be sufficiently liberated to respond to the physiochemical mechanisms of separation.

Modern liberation analysis relies heavily on Automated Mineralogy (AM). Techniques such as Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) and Mineral Liberation Analysis (MLA) have become industry standards[10]. These technologies map the surface of particle cross-sections, providing high-resolution, statistically robust data on:

- **Degree of Liberation:** The percentage of the target mineral that is fully exposed.
- **Mineral Association:** Which gangue minerals are most commonly locked with the target mineral.
- **Textural Complexity:** The physical grain boundaries and intergrowths within the ore.

Implications for Specific Critical Minerals

The extraction of specific critical minerals highlights the necessity of precise liberation data:

- **Lithium (Spodumene):** Hard-rock lithium ores contain spodumene intergrown with quartz and feldspars. Spodumene requires highly controlled grinding; if it is over-ground into ultra-fines, it becomes highly susceptible to misplacement during froth flotation, resulting in significant yield losses[11].
- **Rare Earth Elements (REEs):** Minerals like monazite and bastnäsite often feature highly complex, fine-grained microtextures. AM is frequently used to track how REEs deport across different size fractions, as they are notoriously difficult to liberate without sophisticated stage-grinding circuits[8].

As high-grade critical mineral deposits are depleted, the mining industry is forced to process increasingly complex ores. Grain size and liberation analysis are no longer optional diagnostic tools; they are mandatory for designing efficient, energy-conscious, and economically viable extraction circuits. By utilizing automated mineralogy to precisely map mineral associations, metallurgists can optimize comminution, maximize recovery, and secure the supply chains required for modern technologies.

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