RECOVERY OF RARE EARTH ELEMENTS FROM FERRIC–APATITIC TAILINGS IN CHILE: MINERALOGY, EXTRACTION ROUTES, QUANTITATIVE SEPARATION, LIFE-CYCLE PERFORMANCE AND PROJECT ECONOMICS

Tamara Roblero[160], Andrés Soto-Bubert[161], Roberto Acevedo[162]

https://doi.org/10.66793/intraders15proceeding37

Abstract

Rare earth elements (REEs) have become central to the global energy transition because they enable high-power permanent magnets, efficient electric motors, wind-turbine generators, advanced electronics and key defense technologies. At the same time, the supply chain remains exposed to geopolitical risk and processing bottlenecks because REEs are hosted by accessory minerals and require complex multi-stage separations. This chapter develops a review-style synthesis focused on ferric–apatitic tailings in Chile, particularly deposits associated with iron oxide–apatite (IOA) systems. Building on the technical scope of conceptual-level engineering studies, we integrate: REE geochemistry and mineralogical hosting (apatite-dominant LREE enrichment), quantitative characterization strategies (XRD, XRF, ICP-MS, automated mineralogy and deportment analysis), flowsheet engineering for reprocessing (magnetic preconcentration, classification/desliming, optional apatite flotation, sulfuric-acid leaching, purification of Ca-Fe-phosphate liquors, solvent extraction and/or ion exchange), and precipitation of mixed rare earth carbonate (MREC) as a pragmatic intermediate product. We then connect process design to mass-energy balances, key performance indicators (recovery, TREO upgrading, specific reagent/water/energy use), cradle-to-gate life-cycle metrics (carbon and water footprints), and economic evaluation under uncertainty using Monte Carlo simulation and sensitivity tools. The synthesis supports the technical and environmental feasibility of tailings-based REE recovery in Chile—especially for La-Ce-Nd-Pr-rich streams while identifying the dominant constraints for bankable projects: TREO grade variability, achievable recoveries under impurity-controlled operation, reagent and electricity intensities, and realistic payability for MREC under basket-value pricing. We close by proposing research priorities and strategic actions for Chile to convert tailings from liabilities into critical-minerals assets aligned with circular economy objectives (Binnemans et al., 2013; Gupta & Krishnamurthy, 2005; Chakhmouradian & Wall, 2012; IEA, 2020; COCHILCO, 2021; SERNAGEOMIN, 2023).

Keywords: Rare earth elements; ferric–apatitic tailings; apatite; iron oxide–apatite (IOA); magnetic separation; acid leaching
JEL Code: Q32, L72, Q56, O13, Q58

[160] Facultad de Ingeniería. Universidad San Sebastián. Bellavista 7. 8420524 Santiago. Chile Email: trobleros@correo.uss.cl, ORCID: 0009-0006-1811-5721
[161] Facultad de Ingeniería. Universidad San Sebastián. Bellavista 7. 8420524 Santiago. Chile Email: andres.soto@uss.cl,ORCID: 0000-0002-1127-6809
[162] Facultad de Ingeniería. Universidad San Sebastián. Bellavista 7. 8420524 Santiago. Chile Email: roberto.acevedo.llanos@gmail.com, ORCID: 0000-0001-6847-0285

1. Introduction

The decarbonization of energy and mobility systems has increased demand for rare earth elements (REEs) at a pace that links mineral supply directly to climate and industrial policy. Permanent magnets containing neodymium and praseodymium (often enhanced with dysprosium and terbium for high-temperature performance) are a key example: they enable compact, efficient motors and generators that improve the energy efficiency of electric vehicles and wind turbines. Beyond magnets, REEs support phosphors in lighting and displays, catalysts for refining and emission control, specialized optical glasses, lasers and strategic defense components (Binnemans et al., 2013; IEA, 2020).

Yet REE supply chains face two structural challenges. First, economically exploitable REE deposits are uncommon not because REEs are scarce in the crust, but because they are typically dispersed and concentrated in accessory minerals that require fine grinding and complicated chemical liberation. Second, REE separations are inherently difficult because most lanthanides occur as Ln^{3+} with similar ionic radii and coordination chemistry. Industrial separation therefore relies on subtle thermodynamic differences amplified over many stages of solvent extraction or ion exchange, which increases capital intensity and operational risk (Gupta & Krishnamurthy, 2005; Jordens et al., 2013).

These challenges motivate interest in secondary resources—particularly mine tailings—where material has already been mined, crushed and deposited. Tailings reprocessing can reduce environmental liabilities while creating new products, aligning with circular economy principles and with the growing policy focus on critical minerals. Chile is especially relevant: it has an extensive inventory of tailings deposits, a mature mining sector and increasing institutional attention to valorization of mining wastes. Among tailings types, ferric–apatitic tailings stand out because they retain apatite and magnetite from iron oxide–apatite (IOA) systems, and apatite commonly hosts light rare earth elements (LREEs) through substitution mechanisms controlled by lanthanide contraction and charge compensation (Fleet & Pan, 1995; Chakhmouradian & Wall, 2012).

This chapter is written as a review with an engineering lens. It traces a consistent thread from REE geochemistry to process selection, then from process selection to quantification (balances, KPIs, life-cycle metrics and economics). A central concept is that early-stage projects can reduce risk by targeting intermediate products—especially mixed rare earth carbonate (MREC)—rather than pursuing full separation into individual oxides or metals. MREC can improve market access and financing prospects while enabling progressive learning, piloting and scale-up toward deeper value-chain integration.

2. REE Fundamentals Relevant to Tailings Processing

2.1 Definition and classification.

REEs comprise the lanthanide series (La–Lu) plus yttrium and scandium due to their broadly similar chemistry. For processing, it is useful to group REEs into LREEs and HREEs (and, in some

schemes, MREEs) because mineral hosting and separation behaviors differ. LREEs tend to be hosted by phosphate and carbonate minerals such as apatite, monazite and bastnäsite, whereas HREEs are more associated with xenotime and, in lateritic settings, ion-adsorption clays (Gupta & Krishnamurthy, 2005; Jordens et al., 2013). This mineralogical differentiation has direct implications for how REEs are liberated (cracking or leaching) and how separation circuits are configured.

2.2 Lanthanide contraction, mineral substitution and impurity behavior.

The lanthanide contraction is a systematic decrease in ionic radii across the series caused by poor shielding of 4f electrons. This phenomenon influences both natural fractionation and industrial separation. In apatite, LREEs substitute more readily for Ca^{2+} because their radii more closely match Ca in common coordination environments, whereas progressively smaller HREEs can become less compatible unless specific structural defects or coupled substitutions facilitate incorporation (Shannon, 1976; Fleet & Pan, 1995). In tailings derived from apatite-bearing systems, this tends to create LREE-rich distributions that are beneficial for certain markets (e.g., Nd-Pr magnets) but can also be diluted by La and Ce, which may depress the basket value of mixed products if not managed by downstream commercial strategies (IEA, 2020).

2.3 Separation chemistry as a design constraint.

Because REE separations rely on small chemical differences, the separation endpoint must be chosen strategically. Full separation to individual oxides requires many extraction stages, strict impurity control, large organic inventories and substantial CAPEX. In contrast, producing an intermediate such as MREC requires fewer stages: a circuit that extracts total REEs from leach liquor, scrubs impurities and strips REEs into a clean stream suitable for carbonate precipitation can be technically simpler and financially more realistic for early deployment (Gupta & Krishnamurthy, 2005; Binnemans et al., 2013).

3. Ferric–Apatitic Tailings in Chile: Resource Context and Opportunity

3.1 Tailings as anthropogenic deposits.

Tailings deposits represent already-mined material with potential economic value. Reprocessing can reduce environmental risk (e.g., stability improvement, volume reduction, contaminant removal) while generating revenue streams that help finance remediation. Such “dual-benefit” projects are increasingly discussed internationally, especially for critical elements (Binnemans et al., 2013). In Chile, the national tailings inventory provides a systematic basis to identify candidate deposits, including those associated with iron and phosphate mineralization, and to evaluate infrastructure, water availability, environmental constraints and community context (SERNAGEOMIN, 2023).

3.2 IOA systems and REE hosting in apatite.

Ferric–apatitic tailings typically originate from operations targeting magnetite and/or iron ores associated with apatite. In IOA contexts, apatite is not merely a gangue mineral; it is a potential REE host.

REEs can enter apatite through substitution on Ca sites, with charge compensation via coupled substitutions involving Na, Si, S or vacancies. The consequence for process engineering is that REE recovery is often coupled to phosphate dissolution chemistry, and leach liquors can be rich in Ca and phosphate species, which must be managed to prevent scaling and to maintain SX performance (Fleet & Pan, 1995; Habashi, 1997).

3.3 Variability and the need for geometallurgical frameworks.

Tailings deposit heterogeneity is a primary technical risk. Changes in ore feed, plant operation, reagent regimes and deposition methods over years create variability in TREO grade, mineral associations and grain size distributions. A geometallurgical framework therefore becomes essential: it links spatial domains to process behavior and enables probabilistic propagation of variability into mass balances, life-cycle indicators and project economics. In conceptual studies, this is often implemented through distributions for TREO and recovery parameters used in Monte Carlo simulations, complemented by sensitivity analyses that identify which variables most strongly drive NPV outcomes.

4. Quantitative Characterization: From Sampling to REE Deportment

4.1 Sampling, heterogeneity and representativeness.

Tailings characterization begins with sampling design. Unlike in-situ ore bodies, tailings are hydrodynamically deposited, often leading to sorting by particle size and density. Vertical stratification can arise from changing deposition rates, seasonal operation, or episodic events. Robust sampling should therefore include: vertical profiles (e.g., auger or drilling), lateral transects across the impoundment, and targeted sampling near discharge points versus distal zones. The goal is to quantify both average properties and domain-specific variability.

4.2 Geochemical quantification.

Bulk chemistry is typically determined by XRF for major/minor elements and by ICP-OES/ICP-MS for trace and REE concentrations. For REE evaluation, total rare earth oxides (TREO) and individual element distributions (La, Ce, Pr, Nd, etc.) should be measured to derive basket-value implications. Normalized REE patterns can reveal fractionation between LREE and HREE and provide clues about host phases and potential processing behavior.

4.3 Mineralogical and textural characterization.

Bulk mineralogy (XRD) identifies major phases (magnetite, apatite, silicates), while automated mineralogy (MLA/QEMSCAN) and SEM-EDS reveal liberation, association and fine-scale hosting. This is essential because REEs can be present in trace accessory phases that dominate behavior despite low abundance. For ferric–apatitic tailings, the critical questions include: (i) What fraction of REEs reside in apatite vs accessory phosphates/silicates? (ii) At what grain size is apatite liberated from magnetite and silicates? (iii) Do slimes carry disproportionate REEs due to surface adsorption or fine phosphate

particles?

4.4 Deportment analysis and implications for process selection.

Deportment analysis maps REEs to mineral hosts and size fractions, enabling rational flowsheet selection. If REEs are mainly in apatite, then strategies that preconcentrate apatite (flotation, gravity, size classification) can reduce chemical throughput. If a significant fraction is in monazite/allanite, then leaching may require stronger conditions, and impurity management (including radiological considerations if Th is present) becomes more important. Deportment is also directly linked to expected impurities in the PLS and therefore to SX/IX design constraints. The implications of coexisting minerals and associated impurity elements (e.g., Ca, Fe, Al, Mg, and potential Th/U) for downstream separation and purification are further discussed in Appendix G.

5. Flowsheet Engineering for Tailings-to-MREC: Unit Operations and Design Trade-offs

5.1 Preconcentration logic: reducing chemical footprint.

A principle of sustainable flowsheet design is to reduce the mass entering hydrometallurgy. Magnetic separation is a natural first step in ferric–apatitic tailings because magnetite is abundant and can be removed by LIMS, reducing iron reporting to the leach circuit. WHIMS may further manage paramagnetic phases; however, its value must be evaluated by deportment data: if REEs report mainly with apatite rather than magnetite, WHIMS primarily supports impurity control rather than REE upgrading.

Classification and desliming are often crucial. Slimes can degrade flotation selectivity, increase leach reagent consumption and complicate filtration. Therefore, hydrocyclone classification and careful control of PSD can improve both preconcentration performance and downstream solid–liquid separation.

5.2 Apatite flotation (optional but often strategic).

Where apatite hosts a high fraction of REEs, flotation can be used to produce an apatite-rich concentrate that becomes the primary feed to leaching. Fatty acids are widely used collectors for phosphate flotation, but reagent selection must be integrated with downstream leaching to avoid organic carryover issues. The trade-off is clear: flotation adds circuit complexity and cost, but may substantially reduce leach mass and improve overall economics.

5.3 Acid leaching and liberation of REEs.

Sulfuric acid leaching is commonly considered for phosphate-hosted REEs due to reagent availability and compatibility with sulfate-based downstream chemistry. Key operating variables include acid concentration, temperature, residence time and solid-to-liquid ratio. In apatite-rich feeds, Ca

dissolution and gypsum formation must be managed to prevent scaling and to maintain flowability. In practice, staged leaching and controlled supersaturation can reduce precipitation in reactors and pipelines (Habashi, 1997).

5.4 Purification of Ca-Fe-phosphate liquors.

Purification is often the decisive step for SX stability and product quality. Iron (especially Fe^{3+}) can co-extract into organic phases and reduce selectivity; aluminum and silica can promote gel formation; calcium can scale as gypsum or co-precipitate with carbonate products. Controlled neutralization/hydrolysis is typically used to remove Fe/Al while minimizing REE losses. Calcium control may involve selective precipitation, process integration and sulfate management. Purification design should consider not only chemistry but also solids handling: filterability, thickener sizing and residue stability.

5.5 Solvent extraction and/or ion exchange configuration for MREC.

In the MREC pathway, the goal of SX/IX is not full lanthanide separation but rather total REE extraction, impurity scrubbing and clean stripping. Organophosphorus extractants such as D2EHPA are commonly referenced in the REE industry and provide workable selectivity profiles when impurity levels are controlled (Gupta & Krishnamurthy, 2005). Ion exchange can supplement SX for polishing or for modular, smaller-scale circuits. Circuit designers must manage phase disengagement, crud formation risk, solvent losses, and safety of organic inventories.

5.6 Carbonate precipitation, filtration and drying.

MREC is produced by precipitating REEs as carbonate from a purified REE strip liquor using sodium carbonate or related reagents. The precipitation stage must deliver a solid that is both chemically acceptable (impurity thresholds) and physically manageable (filterable, washable, dryable). Product consistency is essential for commercialization and payability. Drying energy and dust control must also be considered to ensure occupational safety and product handling quality.

Operational design constraints (reclaim strategy, scaling control, and solid–liquid separation bottlenecks) are expanded in Appendix A.

6. Quantitative Separation: From Mixed Products to Individual Oxides (and Why It Matters)

REE value chains are strongly shaped by separation complexity. Producing separated oxides and metals generally requires multi-stage solvent extraction with dozens to hundreds of stages, strict impurity control and high capital intensity. For a tailings-based project, this level of complexity can be misaligned with feed variability and early-stage uncertainty. MREC therefore offers an intermediate endpoint: it captures REEs in a transportable, commercializable form while limiting stage count and CAPEX. However, MREC economics depend on basket value: if La and Ce dominate, payability may be reduced; if Nd-Pr content is high, payability improves. Thus, quantitative separation is not only a chemical

problem but also a commercial optimization problem. Because MREC payability is specification- and basket-value-driven, impurity thresholds and market alignment are detailed in Appendix B

From an engineering perspective, separation design should be framed as an optimization over: (i) target product slate (MREC vs separated REO), (ii) achievable purity and impurity control costs, (iii) stage count and solvent inventory, and (iv) netback price after transportation, refining charges and contractual deductions. This framing makes it possible to choose a rational development pathway—starting with MREC and progressing to deeper separation only once reliable feed characterization and stable operation have been demonstrated.

7. Mass and Energy Balances: Connecting Mineralogy to KPIs

Mass and energy balances translate geological potential into plant-level requirements. A first-order mass balance for MREC production highlights the dominant drivers: tailings throughput, TREO grade, overall recovery and target product grade. Even moderate changes in TREO grade can strongly affect throughput and therefore equipment sizing, energy demand and reagent consumption. This is why preconcentration can be disproportionately valuable: it increases effective TREO to leach and reduces chemical throughput.

Energy demand is typically dominated by pumping and agitation (especially where large liquid volumes are processed), solvent extraction circulation, filtration, and drying. Tailings may already be fine, reducing comminution energy; however, if apatite is locked in coarser particles or composites, regrinding may be necessary. Energy intensity then links directly to carbon footprint under Chile's electricity mix, which is why energy-efficient solids handling (high-density slurry transport, thickening, filtration) can improve both economics and LCA metrics.

For benchmarking, KPIs should be reported with clear system boundaries. Recommended KPIs include: global REE recovery; enrichment factor; TREO grade at key points; specific acid consumption (per tonne tailings and per tonne MREC); specific carbonate consumption; water use and recirculation ratio; kWh per tonne MREC; CO_2e per tonne MREC; and unit OPEX (USD per kg REO equivalent). Such KPIs enable transparent comparison with international projects and highlight where optimization has the greatest leverage. For reproducibility and benchmarking, standardized variables to report are listed in Appendix F

Process-intensification levers that reduce acid and electricity intensity are summarized in Appendix D. Also an illustrative grade–recovery–throughput relationship that demonstrates the scale sensitivity of MREC production is provided in Appendix E.

8. Environmental Performance: Life-Cycle Assessment and Tailings-Specific Benefits

Life-cycle assessment (LCA) is essential to evaluate whether tailings-based REE recovery genuinely reduces environmental burdens relative to primary mining. The cradle-to-gate boundary

typically includes tailings reclaim, transport within site, processing, reagent production, electricity, water intake, residue management, and product drying. Tailings projects often benefit from avoiding upstream activities such as drilling, blasting and overburden movement; however, hydrometallurgy can dominate impacts if reagent and energy intensities are high (Binnemans et al., 2013).

The principal LCA drivers for REE circuits are commonly electricity and acid production. Therefore, mitigation focuses on reducing leach mass (preconcentration), improving energy efficiency, integrating heat, and maximizing water recirculation. Water footprint is particularly important in Chile; closed-loop systems and robust thickening/filtration reduce freshwater intake. Tailings-specific benefits may include improved stability of the remaining deposit, reduced stored mass, and reduced long-term risk—benefits that can be meaningful for social license even when not fully captured by standard LCA indicators.

A critical design point is residue management. Tailings reprocessing generates new residues (leached solids, neutralization precipitates, gypsum). These must be stabilized and disposed of responsibly to avoid creating new liabilities. An integrated environmental strategy should therefore include residue characterization, leachability testing, and long-term storage design consistent with Chilean regulation and best practice.

The environmental implications of these intensification strategies are further contextualized in Appendix D.

9. Economic Evaluation Under Uncertainty: Monte Carlo, Sensitivity and Decision-Making

Tailings-based REE projects face uncertainty in feed grade, recoveries, reagent intensity, electricity costs and product prices. Deterministic cash-flow models can obscure this risk. Monte Carlo simulation provides a more decision-relevant view by producing distributions of NPV and IRR. Key inputs commonly treated probabilistically include TREO grade, recovery, REE basket price, CAPEX, OPEX, plant availability, and discount rate assumptions. A worked quantitative example illustrating how grade and recovery assumptions propagate into throughput requirements and, consequently, economic outcomes is provided in Appendix E.

Sensitivity analysis (e.g., Spearman rank correlations, tornado charts) helps identify dominant drivers. In many REE projects, price and recovery dominate, while TREO grade strongly influences throughput, reagent consumption and energy use. This insight is useful: it directs optimization toward improving metallurgical recovery and toward commercial strategies that improve netback prices. It also clarifies the economic value of preconcentration, because upgrading reduces exposure to low-grade scenarios and can flatten OPEX sensitivity.

Commercialization of MREC involves practical constraints: impurity thresholds, moisture limits, payability formulas, refining charges and logistics. Off-take agreements can materially reduce financing

risk by stabilizing revenue assumptions. Therefore, commercialization strategy should be treated as part of the engineering design rather than an afterthought: purification and product finishing steps can increase payability and reduce discounting, potentially shifting the NPV distribution toward viability. Because netback assumptions depend critically on basket composition, impurity compliance, and contractual refining terms, the specification-driven determinants of MREC payability are examined in greater detail in Appendix B.

10. Benchmarking and Strategic Positioning: Lessons from Comparable Projects

Benchmarking supports realistic design by comparing candidate projects to international analogs. However, direct comparisons must respect mineralogical differences. Ferric–apatitic tailings differ from ionic clay deposits (which often use ammonium sulfate leaching and ion exchange) and from carbonatites (which may process bastnäsite/monazite concentrates). Nevertheless, comparable unit operations exist: magnetic separation, phosphate cracking, solvent extraction and carbonate precipitation.

Benchmark OPEX for REE projects varies widely with scale, energy prices and reagent intensity. Scale effects are especially decisive: small plants often suffer high unit CAPEX and OPEX, while large plants require greater capital commitment and robust infrastructure. For Chile, the strategic implication is that pilot validation and staged scale-up can reduce risk. Partnerships with technology providers and buyers can accelerate learning, while integration with national critical-minerals strategies can improve the policy environment for investment (COCHILCO, 2021; USGS, 2024).

11. Policy, Regulation and Circular Economy: A Chilean Roadmap

Chile’s opportunity in tailings-based REE recovery sits at the intersection of mining engineering, environmental governance and industrial policy. Tailings reprocessing can contribute to circular economy goals by extracting value from previously discarded material and reducing long-term liabilities. To realize this opportunity, coordination among technical agencies and policy bodies is critical, including consistent frameworks for tailings characterization, permitting, and environmental monitoring (SERNAGEOMIN, 2023).

Social license is an equally important dimension. Communities may support reprocessing when it demonstrably reduces risk and improves environmental performance, but trust depends on transparency. Credible indicators—such as quantified reductions in stored mass, improved stability metrics, water balances and carbon footprints—help align stakeholder expectations. Projects should also avoid shifting risk: reprocessing residues must be managed so that new storage forms do not recreate historical tailings problems.

A staged roadmap can be proposed: (i) national screening of ferric–apatitic tailings for TREO and

host mineralogy; (ii) pilot programs to validate leaching and impurity control; (iii) commercialization pilots for MREC; and (iv) longer-term movement downstream toward separated oxides if market conditions and partnerships justify investment. This roadmap aligns with a prudent development strategy under uncertainty while building domestic capability in critical-minerals processing. A staged implementation roadmap under Chile's tailings governance framework is expanded in Appendix C.

12. Conclusions and Research Priorities

Ferric–apatitic tailings in Chile represent a credible secondary resource for REE recovery, particularly for LREEs hosted in apatite. The most pragmatic early pathway integrates magnetic preconcentration, classification/desliming, acid leaching, purification of Ca-Fe-phosphate liquors, and SX/IX to produce MREC. Environmental performance can be favorable compared with primary mining routes, provided that reagent and energy intensities are controlled and that residues are responsibly managed. Economic viability is primarily constrained by TREO grade variability, achievable recoveries, electricity and reagent costs, and product netback prices under basket-value payability.

Priority research needs include: high-resolution deportment studies in Chilean ferric–apatitic tailings; pilot-scale validation of leaching with gypsum and impurity control; SX/IX robustness under real-liquor variability; product specification studies for MREC with realistic buyer requirements; and integrated techno-economic-environmental optimization using probabilistic modeling. Addressing these priorities can move tailings-based REE recovery from conceptual feasibility to investable projects, supporting Chile's strategic role in critical-minerals supply chains.

References

Binnemans, K., Jones, P. T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., & Buchert, M. (2013). Recycling of rare earths: A critical review. *Journal of Cleaner Production, 51*, 1–22.

Chakhmouradian, A. R., & Wall, F. (2012). Rare earth elements: Minerals, mines, magnets. *Elements, 8*(5), 333–340.

Chilean Copper Commission. (2021). *Tierras raras en Chile: Potencial, desafíos y oportunidades*. COCHILCO.

European Commission. (2020). *Critical raw materials resilience: Charting a path towards greater security and sustainability*. European Commission.

Fleet, M. E., & Pan, Y. (1995). Site preference of rare earth elements in fluorapatite. *American Mineralogist, 80*, 329–335.

Greenwood, N. N., & Earnshaw, A. (1997). *Chemistry of the elements* (2nd ed.). Butterworth-Heinemann.

Gupta, C. K., & Krishnamurthy, N. (2005). *Extractive metallurgy of rare earths*. CRC Press.

Habashi, F. (1993). *A textbook of hydrometallurgy*. Métallurgie Extractive Québec.

Habashi, F. (1997). *Handbook of extractive metallurgy*. Wiley-VCH.

Humphries, M. (2013). *Rare earth elements: The global supply chain*. Congressional Research Service.

International Energy Agency. (2020). *The role of critical minerals in clean energy transitions*. International Energy Agency.

Jordens, A., Cheng, Y. P., & Waters, K. E. (2013). A review of the beneficiation of rare earth element-bearing minerals. *Minerals Engineering, 41*, 97–114.

Lottermoser, B. G. (2010). *Mine wastes: Characterization, treatment and environmental impacts* (3rd ed.). Springer.

Mancheri, N. A., Sundaresan, L., & Chandrashekar, S. (2019). Dominating the supply of critical minerals: Challenges for a low-carbon future. *Resources Policy, 62*, 308–315.

Schüler, D., Buchert, M., Liu, R., Dittrich, S., & Merz, C. (2011). *Study on rare earths and their recycling*. Öko-Institut.

Servicio Nacional de Geología y Minería. (2023). *Catastro nacional de depósitos de relaves*. SERNAGEOMIN.

Shannon, R. D. (1976). Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides. *Acta Crystallographica Section A, 32*, 751–767.

U.S. Department of Energy. (2011). *Critical materials strategy*. U.S. Department of Energy.

United States Geological Survey. (2024). *Mineral commodity summaries 2024: Rare earths*. U.S. Geological Survey.

World Bank. (2020). *Minerals for climate action: The mineral intensity of the clean energy transition*. World Bank.

Appendix A. Engineering Design Notes for Ferric–Apatitic Tailings REE Circuits (Expanded Review)

A1. Practical feed preparation and reclaim considerations.

Tailings reclamation is often treated as a minor upstream step, yet it can dominate operational performance and costs. Reclaim methods (hydraulic mining, dredging, dry excavation) influence feed density, PSD, and water chemistry. Hydraulic reclaim may introduce high water volumes and dissolved salts that affect leach chemistry, while dry reclaim can increase dust and require robust conditioning. For ferric–apatitic tailings, reclaim strategy should be explicitly connected to downstream thickening and filtration capacity, because high-density slurry handling reduces pumping energy and make-up water demand.

A2. Mineralogical drivers of comminution requirements.

Tailings are frequently “already ground,” but apatite can remain locked in composite particles with magnetite and silicates. Automated mineralogy is therefore used not only for deportment, but also for liberation modeling. If liberation of apatite occurs primarily below a certain size fraction, targeted

regrinding of coarse streams (rather than full-stream regrind) can reduce energy intensity. This selective grinding logic is consistent with best-practice comminution design and can improve both OPEX and LCA metrics.

A3. Process water chemistry and scaling.

Sulfate systems are prone to gypsum ($CaSO4{\cdot}2H2O$) precipitation. Scaling risk is driven by ionic strength, temperature, pH and residence time. In sulfate-rich circuits, controlling supersaturation via staged reagent addition, temperature management and seed recycling can reduce uncontrolled precipitation. Because scaling directly affects plant availability, it should be represented in reliability assumptions (availability distributions) when performing Monte Carlo simulations.

A4. Solid–liquid separation as a bottleneck.

Many REE flowsheets fail economically not in extraction but in filtration and washing. Tailings fines can yield slow filtration and high moisture in products, increasing drying energy and reducing payability. Engineering mitigation includes flocculant optimization, pre-thickening, use of counter-current decantation (CCD), and selection of filter technology appropriate for the PSD and mineralogy. In review terms, solid–liquid separation should be discussed as a core design constraint rather than an auxiliary unit operation.

A5. Expanded discussion of leaching chemistry for apatite-hosted REEs

In apatite-hosted systems, the leach objective is to dissolve phosphate matrices and release REE^{3+} while controlling co-dissolution of impurities. Sulfuric acid is often attractive due to cost and availability, yet chloride systems may offer advantages in certain impurity regimes. In sulfate leaching, gypsum formation can remove calcium from solution, which may be beneficial for downstream SX; however, uncontrolled precipitation can trap REEs and create filtration challenges. In chloride leaching, calcium remains more soluble, which can increase the burden on purification but may simplify scaling control. Therefore, an engineering review should not prescribe a single chemistry universally; instead, it should propose a decision framework based on liquor composition, local reagent economics, water chemistry constraints and the impurity tolerance of the selected separation system.

Leach kinetics are influenced by temperature, acid strength and particle size. Higher temperatures accelerate dissolution but increase evaporation and may change precipitation equilibria. Because tailings projects often aim to minimize energy input, identifying a “minimum-energy operating window” that still achieves acceptable recovery is valuable. In practice, this is done through factorial testing or response surface methodology in pilot programs, but at review level it is sufficient to emphasize which variables are typically dominant and how they interact (Habashi, 1997; Gupta & Krishnamurthy, 2005).

A6. Quantitative separation: stage design concepts for SX (review-level)

A conceptual SX design for MREC production can be described in three blocks: extraction, scrubbing and

stripping. In extraction, the organic phase loads REEs from the PLS. In scrubbing, co-extracted impurities (Fe, Al, Ca, potentially Mn) are washed out under controlled conditions. In stripping, REEs are transferred to an aqueous stream suitable for precipitation. The performance of each block depends on distribution coefficients, phase ratios, temperature, and the chemistry of the aqueous phase. Importantly, stable phase disengagement and avoidance of crud formation are as important as equilibrium selectivity, especially with real tailings liquors.

For review purposes, it is useful to emphasize that stage count grows rapidly when higher purity is required. This "exponential complexity" is the core argument for MREC as an early product. Once a stable MREC product and supply chain are established, additional separation stages can be justified economically if downstream partnerships exist and if the incremental value exceeds incremental cost and risk (Gupta & Krishnamurthy, 2005; Binnemans et al., 2013).

A7. Expanded life-cycle indicators and reporting guidance

A robust LCA discussion benefits from clear functional units and transparent boundaries. Recommended functional units include: per tonne of tailings processed, per tonne of MREC produced, and per kilogram of REO equivalent. Reporting multiple units prevents misleading comparisons, because projects with low grades may appear "efficient per tonne tailings" but not per kilogram product (or vice versa).

In addition to climate change potential (kg CO2e), water consumption (m3), and energy use (kWh), other indicators can be relevant: acidification potential, eutrophication potential (especially for phosphate releases), and human toxicity potential. Even when not quantified, the review should note that phosphate-bearing circuits require careful management to avoid eutrophication risk in discharge scenarios. Tailings reprocessing projects should therefore integrate water treatment and containment into design from the beginning, not as a late add-on.

A8. Expanded techno-economic modeling structure

A standard techno-economic model links unit operations to consumptions and costs. For tailings-based REE recovery, a practical structure includes: (i) upstream reclaim and conditioning costs; (ii) comminution and classification energy; (iii) reagent costs for flotation (if included), leaching and purification; (iv) SX/IX consumables (extractant, diluent, resin, make-up rates); (v) utilities (electricity, water, steam/heat); (vi) residue management costs; and (vii) product logistics. CAPEX is typically structured by major plant areas and scaled by throughput, with contingencies reflecting early-stage uncertainty.

Monte Carlo simulation uses distributions for the most uncertain inputs, but should also include correlations (e.g., lower grades may correlate with higher unit reagent consumption due to higher gangue). Even simplified correlation assumptions improve realism. Outputs include NPV distributions, probability of negative NPV, and value-at-risk style metrics. Sensitivity analysis then guides where pilot

programs should focus to reduce uncertainty most efficiently.

Appendix B. Rare Earth Applications and Specification-Driven Processing (Expanded Review)

B1. Permanent magnets and the Nd–Pr value driver.

The most decisive demand driver for many REE projects is the magnet sector. Nd–Fe–B magnets provide high energy density and allow size reduction and efficiency gains in motors and generators. Pr is often co-produced with Nd and can substitute in magnet compositions. Dy and Tb are added in smaller quantities to improve high-temperature coercivity. Because market pricing is strongly influenced by magnet demand, Nd and Pr often dominate basket value even when they are a minority of total REE mass in an LREE-rich product. This directly affects the economic attractiveness of ferric–apatitic tailings, where LREEs are expected to predominate (IEA, 2020).

Processing implication: the circuit must aim not only for high total TREO recovery but also for product purity consistent with magnet feedstock requirements (low Ca, Fe, Al, P). Even if MREC is sold for further refining, buyers will discount products with excessive impurities that raise their own refining costs.

B2. Catalysts, polishing powders and the La–Ce volume reality.

La and Ce historically dominate volume in many LREE deposits and remain important for catalysts and polishing powders. For tailings-derived MREC, a high La–Ce fraction can reduce payability if the buyer's downstream market is magnet-focused. However, diversified off-take channels (catalysts/polishing) can improve netbacks. Therefore, a strategic commercialization plan should be presented alongside the process description, including potential buyers and product qualification routes.

B3. Phosphors, optics and niche uses.

Eu, Tb and Y are important for phosphors and optical applications, while Er, Yb and other HREEs are used in lasers and fiber optics. Ferric–apatitic tailings are not expected to be HREE-rich, but trace HREE content can still matter for refining behavior and may add marginal value. At review level, the key point is that the "application map" of REEs explains why certain elements command high prices and why mixed products are priced by basket value rather than by total TREO alone.

B4. Product specification logic for MREC.

MREC specifications commonly include minimum TREO content, maximum moisture, and thresholds for impurities such as Ca, Fe, Al, Mg, Na, and sometimes radionuclides. In practice, "specification-driven processing" means that purification and washing/drying are not optional: they are integral to achieving payability and avoiding rejection. Therefore, unit operations that improve filterability and reduce impurity carryover can have an outsized economic effect.

Appendix C. Expanded Discussion of Chilean Context: Tailings Governance and Implementation Pathways

C1. Tailings inventory and screening.

Chile's tailings inventory (SERNAGEOMIN, 2023) enables systematic screening of deposits for reprocessing. For REE recovery, screening criteria should include: association with apatite or phosphate mineralization; presence of magnetite (beneficial for magnetic preconcentration); deposit accessibility; water availability and constraints; proximity to infrastructure; and community/environmental sensitivities. The screening stage also benefits from rapid analytical methods to prioritize deposits for detailed study.

C2. Implementation pathways and staged development.

A staged approach reduces risk and matches the learning curve. Stage 1 focuses on characterization and variability mapping; Stage 2 on bench-scale metallurgical testing (preconcentration, leaching, purification); Stage 3 on pilot-scale demonstration including solid–liquid separation and product quality; Stage 4 on modular commercialization of MREC; Stage 5 on expansion toward separated oxides if justified. Each stage should have explicit decision gates and success criteria, including target recoveries, impurity thresholds, and cost ranges.

C3. Integration with circular economy and remediation.

Tailings reprocessing can be designed to contribute to remediation by reducing mass, improving stability and removing reactive phases. However, reprocessing also creates new residues. The project should therefore define an integrated residue management plan, including stabilization, deposition method and long-term monitoring. Communicating these plans transparently is essential for social license.

C4. Skills and innovation ecosystem.

Chile's mining ecosystem provides strong capabilities in beneficiation and hydrometallurgy, yet REE-specific separation expertise is less mature. Collaboration among universities, research centers and industry partners can accelerate knowledge transfer, especially in SX/IX design and product qualification. This context supports the chapter's emphasis on MREC as a practical early product: it creates a platform for capability building without requiring immediate investment in full separation plants.

Appendix D. Process Intensification and Optimization Opportunities

D1. Selective upgrading to reduce acid footprint.

Because acid production and use frequently dominate both OPEX and carbon footprint, strategies that reduce leach mass flow have high leverage. These include improved magnetic separation, optimized desliming, and, where justified, apatite flotation. In addition, selective regrinding of coarse composites (instead of whole-stream regrind) can improve liberation with lower energy use.

D2. Reagent recycling and circuit closure.

Circuit closure through recycling of process water and partial recovery of reagents can reduce both cost and environmental burden. For example, optimizing sulfate balance and managing dissolved solids can enable higher water recirculation rates. Organic solvent management (reducing losses, improving phase

separation) reduces both OPEX and environmental risk.

D3. Digitalization and control.

Modern plants increasingly use sensors and control strategies to stabilize operation under variable feed. For tailings reprocessing, online monitoring of density, pH, conductivity, and potentially key elemental proxies can help control leach conditions and prevent scaling events. While detailed control design is beyond review scope, the chapter can highlight that stability under variability is a primary determinant of availability—and therefore of economic performance.

D4. Uncertainty-focused piloting.

Pilot testing should be designed not only to maximize average recovery, but to characterize variability and robustness. Testing multiple feed domains and stress-testing impurity regimes provides better inputs for Monte Carlo models and reduces the risk of over-optimistic feasibility conclusions.

Appendix E. Quantitative Worked Example: From Tailings Grade to Plant Throughput (Illustrative)

This appendix provides an illustrative, review-level calculation to connect grade and recovery to the scale of operation required for MREC production. The purpose is not to claim a specific deposit's grade, but to show how sensitive throughput is to TREO and overall recovery.

Assume a tailings feed with TREO_feed = 1,000 ppm (0.10% TREO by mass). Suppose the integrated circuit (preconcentration + leaching + purification + SX/IX + precipitation) achieves Recovery_total = 65% of TREO into the final product. If the target product is MREC with TREO_MREC = 40% (typical of many mixed carbonate products), then the mass of MREC obtained per tonne of tailings is:

MREC_per_tailing = (TREO_feed × Recovery_total) / TREO_MREC

= (0.0010 × 0.65) / 0.40

= 0.001625 t MREC per t tailings

≈ 1.63 kg MREC per tonne of tailings.

To produce 10,000 t/y of MREC under these assumptions, annual tailings throughput would be approximately:

Tailings_throughput ≈ 10,000 / 0.001625 ≈ 6.15 million t/y.

If TREO_feed increases to 1,500 ppm (0.15%) through preconcentration or favorable domains, keeping recovery and product grade constant: MREC_per_tailing = (0.0015 × 0.65) / 0.40 = 0.0024375 t/t = 2.44 kg/t, which reduces throughput to ≈ 4.10 million t/y for the same product output.

These simple relations explain why preconcentration is central to both economics and environmental performance: upgrading the feed reduces not only plant size and CAPEX but also reagent and energy intensities per tonne of product. Conversely, if recovery drops due to impurity control issues or scaling

events, the required throughput increases sharply, and economics can deteriorate.

For cost modeling, the same logic applies to reagent intensity. If specific acid consumption is expressed per tonne of tailings (e.g., kg H2SO4/t tailings), then the specific acid per tonne of MREC is amplified by the inverse of MREC_per_tailing. Therefore, modest improvements in feed grade or recovery can yield large reductions in reagent consumption per product unit—often the dominant driver of OPEX and LCA outcomes in hydrometallurgical REE circuits (Habashi, 1997; Gupta & Krishnamurthy, 2005).

Appendix F. Typical Operating Windows and Variables to Report (Review Guidance)

In early-stage studies and in published literature, inconsistent reporting often prevents meaningful benchmarking. For ferric–apatitic tailings projects, the following operating variables should be systematically reported:

F1. Feed and preconcentration.

Particle size distribution (d10, d50, d90), mineralogy (apatite %, magnetite %), liberation metrics, and mass pull/recovery of preconcentration steps (LIMS/WHIMS and/or flotation).

F2. Leaching.

Acid type and concentration, temperature, residence time, solid-to-liquid ratio, agitation regime, and the extent of gypsum formation or other precipitates. Report both dissolved REE fraction and dissolved impurity fractions (Ca, Fe, Al, Mg, P).

F3. Purification.

Neutralization reagent, pH setpoints, temperature, residence time, precipitated solids composition, and REE losses in precipitates. Report filterability and solid–liquid separation performance.

F4. SX/IX.

Extractant type, diluent, phase ratio, number of stages (or column volumes), scrubbing conditions, stripping conditions, organic losses, and stability indicators (crud formation, phase disengagement times).

F5. Precipitation and product.

Carbonate reagent type, pH/temperature control, precipitation yield, washing protocol, moisture after filtration, drying conditions, and final product composition (TREO %, individual REE distribution, impurity levels).

F6. Environmental metrics.

Electricity use (kWh), acid and reagent use (kg), water balance (m3 intake vs recycle), and residue generation (kg/t tailings and kg/t product). Reporting these variables enables credible life-cycle comparisons and supports transparent techno-economic evaluation.

Including these items in a book chapter is valuable because it transforms a conceptual review into a reproducible framework that other researchers and practitioners can apply to different tailings deposits.

Appendix G. Separation of REEs from Coexisting Minerals and Elements in Tailings (Expanded

Review)

Ferric–apatitic tailings rarely contain only REE-bearing phases; they typically contain magnetite, apatite, and a variety of silicates and oxide phases that carry elements of economic interest (Fe, P, potentially Ti) as well as elements that complicate hydrometallurgy (Ca, Al, Mg, Si). A technically mature review should explicitly discuss how coexisting minerals affect REE recovery and how they can be managed or valorized.

G1. Iron phases (magnetite/hematite) and their dual role.

Magnetite is often the dominant iron phase in IOA systems and is easily recovered by LIMS. From a REE perspective, removing magnetite before leaching reduces iron dissolution and downstream purification burden. From a circular-economy perspective, recovered magnetite can potentially be marketed as a by-product if quality meets specifications. However, if apatite is intergrown with magnetite, aggressive magnetite recovery can reduce REE recovery unless liberation is adequate. Therefore, the engineering optimum is not "maximum magnetite recovery" but "maximum value recovery," which requires liberation-aware design.

G2. Phosphate as both opportunity and constraint.

Apatite is central because it hosts REEs and contributes phosphorus. Phosphate dissolution produces liquors rich in Ca and phosphate species, which can cause scaling, increase neutralization demand and influence solvent extraction behavior. Yet phosphate also offers a co-product opportunity: under some flowsheets, phosphate can be recovered as a fertilizer precursor. Whether phosphate co-recovery is realistic depends on impurity levels and the cost of additional purification. For early-stage projects, the MREC pathway often prioritizes REEs, while phosphate management is treated as a constraint; later, co-product strategies can be explored to improve project economics.

G3. Silicates and the silica-gel problem.

Silicate minerals can release silica during acid leaching, especially under aggressive conditions. Silica gel formation is problematic because it increases viscosity, reduces filtration rates and can trap REEs. Mitigation strategies include milder leach conditions, pre-treatment steps, pH control and additives that reduce polymerization. In many projects, the practical approach is to avoid operating windows where silica gel formation becomes significant.

G4. Aluminum and magnesium in purification and SX stability.

Al and Mg can remain in solution and affect extraction equilibria and phase separation. Controlled neutralization can remove a portion of Al, but excessive neutralization risks REE co-precipitation. This reinforces the need for optimization: purification is a multi-objective problem where the target is "maximum REE retention at acceptable impurity removal," not maximum impurity removal.

G5. Thorium and uranium (where relevant).

Some REE-bearing minerals (notably monazite) can contain Th and, less commonly, U. If ferric–apatitic tailings contain monazite at meaningful levels, radiological considerations become central for permitting and product acceptance. Even when levels are low, buyers may require documentation. Therefore, characterization programs should include Th/U assays and mineral host identification, and purification circuits should be evaluated for their ability to segregate radionuclides into residues rather than into the product.

G6. Implications for "quantitative separation."

The separation challenge is therefore broader than "separating REEs from each other." It also includes separating REEs from Ca, Fe, Al, Mg and potential radionuclides. From a process-systems perspective, achieving a saleable MREC is the first quantitative separation milestone; only after that milestone does it become rational