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ELEMENTOS TERRAS RARAS: FUNDAMENTOS, RECURSOS MINERAIS E TECNOLOGIAS DE PROCESSAMENTO-UMA REVISÃO NARRATIVA

RARE EARTH ELEMENTS: FUNDAMENTALS, MINERAL RESOURCES, AND PROCESSING TECHNOLOGIES-A NARRATIVE REVIEW

ELEMENTOS DE TIERRAS RARAS: FUNDAMENTOS, RECURSOS MINERALES Y TECNOLOGÍAS DE PROCESAMIENTO-UNA REVISIÓN NARRATIVA

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Resumo

Os elementos terras raras são utilizados em ímãs permanentes, catalisadores, materiais ópticos e outras tecnologias, mas sua recuperação exige processos adaptados a recursos minerais bastante distintos. Esta revisão narrativa examina suas características químicas, os principais minerais portadores e contextos geológicos e as operações empregadas no beneficiamento, na extração e na recuperação de produtos. A literatura científica e informações geológicas oficiais foram sintetizadas qualitativamente, com ênfase em processamento mineral e exemplos relevantes para o Brasil. A discussão distingue os recursos que contêm minerais específicos de terras raras dos regolitos nos quais uma parcela apreciável dos elementos é trocável nas superfícies minerais. Nos minérios cristalinos, a liberação e as diferenças de densidade, susceptibilidade magnética e química superficial orientam a aplicação da concentração gravítica, da separação magnética e da flotação. Nas argilas de adsorção iônica, o inventário trocável e o transporte das soluções podem ser mais importantes que a concentração mineral convencional. A decomposição ácida ou alcalina, a lixiviação salina, a remoção de impurezas, a extração por solventes, a troca iônica e a precipitação desempenham

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funções distintas e devem ser avaliadas como uma sequência integrada. Os resultados publicados mostram que uma extração elevada em determinada operação não implica necessariamente alta recuperação a partir da alimentação original ou pureza suficiente do produto final. As principais limitações incluem intercrescimentos minerais finos, dissolução da ganga, contaminação por alumínio e ferro, recirculação de reagentes e gestão de radionuclídeos naturais, quando presentes. Os recursos brasileiros associados a carbonatitos, materiais com xenotima e depósitos intemperizados demonstram a necessidade de desenvolvimento específico para cada depósito. A seleção dos processos deve combinar evidências mineralógicas, balanços por elemento e requisitos dos produtos, avaliando o desempenho ambiental da rota completa.

Palavras-chave: elementos terras raras; mineralogia de processo; beneficiamento; argilas de adsorção iônica; hidrometalurgia.

Abstract

Rare earth elements support permanent magnets, catalysts, optical materials and other technologies, but their recovery requires processes adapted to markedly different mineral resources. This narrative review examines their chemical characteristics, principal mineral hosts and geological settings, and the operations used for beneficiation, extraction and product recovery. Scientific literature and official geological information were synthesized qualitatively, with emphasis on mineral processing and examples relevant to Brazil. The discussion distinguishes resources containing discrete rare earth minerals from regolith in which an appreciable fraction of the elements is exchangeable at mineral surfaces. For crystalline ores, liberation and differences in density, magnetic susceptibility and surface chemistry govern the application of gravity concentration, magnetic separation and flotation. For ion-adsorption clays, exchangeable inventory and solution transport can be more important than conventional mineral concentration. Acid or alkaline decomposition, salt leaching, impurity removal, solvent extraction, ion exchange and precipitation perform distinct functions and must be evaluated as an integrated sequence. Published results show that high extraction in an individual operation does not necessarily imply high recovery from the original feed or a sufficiently pure final product. Important limitations include fine mineral intergrowths, gangue dissolution, aluminum and iron contamination, reagent recirculation and the management of naturally occurring radionuclides where present. Brazilian carbonatite-related resources, xenotime-bearing materials and weathered deposits illustrate the need for deposit-specific development. Process selection should therefore combine mineralogical evidence, element-specific mass balances and downstream product requirements, with environmental performance assessed across the complete route.

Keywords: rare earth elements; process mineralogy; beneficiation; ion-adsorption clays; hydrometallurgy.

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Resumen

Los elementos de tierras raras se utilizan en imanes permanentes, catalizadores, materiales ópticos y otras tecnologías, pero su recuperación requiere procesos adaptados a recursos minerales muy diferentes. Esta revisión narrativa examina sus características químicas, los principales minerales portadores y contextos geológicos, y las operaciones empleadas en el beneficio, la extracción y la recuperación de productos. La literatura científica y la información geológica oficial disponibles se sintetizaron cualitativamente, con énfasis en el procesamiento mineral y ejemplos relevantes para Brasil. Se distinguen los recursos que contienen minerales específicos de tierras raras de los regolitos en los que una fracción apreciable de los elementos es intercambiable en las superficies minerales. En los minerales cristalinos, la liberación y las diferencias de densidad, susceptibilidad magnética y química superficial orientan la concentración gravimétrica, la separación magnética y la flotación. En las arcillas de adsorción iónica, el inventario intercambiable y el transporte de las soluciones pueden ser más importantes que la concentración mineral convencional. La descomposición ácida o alcalina, la lixiviación salina, la eliminación de impurezas, la extracción por solventes, el intercambio iónico y la precipitación cumplen funciones diferentes y deben evaluarse como una secuencia integrada. Los resultados publicados muestran que una extracción elevada en una operación no implica necesariamente una alta recuperación desde la alimentación original ni una pureza suficiente del producto final. Las limitaciones incluyen intercrecimientos minerales finos, disolución de ganga, contaminación por aluminio y hierro, recirculación de reactivos y gestión de radionucleidos naturales cuando están presentes. Los recursos brasileños asociados a carbonatitas, los materiales con xenotima y los depósitos meteorizados ilustran la necesidad de un desarrollo específico para cada depósito. La selección de procesos debe combinar evidencia mineralógica, balances por elemento y requisitos de los productos, evaluando el desempeño ambiental de la ruta completa.

Palabras clave: elementos de tierras raras; mineralogía de procesos; beneficio de minerales; arcillas de adsorción iónica; hidrometalurgia.

1. Introduction

Rare earth elements (REEs) are constituents of materials whose performance depends on magnetic, optical, catalytic or alloying properties that are difficult to reproduce through simple substitution. Their use in electric motors, generators, chemical catalysts, polishing agents and electronic devices connects mineral production with several industrial sectors. The group nevertheless comprises elements with different applications and geological distributions. A deposit rich in cerium and lanthanum cannot be assumed to supply dysprosium or terbium in

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comparable proportions, and the total rare earth content alone is an incomplete measure of a resource's technological relevance (Goodenough et al.).

The principal processing challenge is to convert a heterogeneous mineral assemblage into products that meet specific compositional requirements. This conversion usually involves several separations at different scales. Beneficiation separates particles according to physical or surface properties; decomposition and leaching transfer elements from a solid into solution; purification removes contaminants and partitions chemically similar REEs. Each step changes the composition and physical characteristics of the stream entering the next operation. A useful review of REE production must therefore connect these operations instead of treating their reported efficiencies as independent indicators of success (Jordens et al., “A Review”; Xie et al.).

Mineralogy creates particularly large differences among potential feedstocks. Bastnaesite, monazite and xenotime contain REEs within crystal structures, whereas some weathered resources contain hydrated REE ions held at mineral surfaces. These occurrence modes require different extraction mechanisms. Comminution and flotation can be central to a hard-rock ore, while a clay deposit may be processed principally by screening, ion-exchange leaching and solution recovery. Even within weathered materials, exchangeable REEs may coexist with refractory phosphate grains. The presence of clay consequently does not demonstrate that all REEs can be extracted under mild saline conditions (Borst et al.; Cunningham et al.).

Research has expanded from established mineral concentrates toward complex ores, mine tailings and solutions already generated by mining operations. These materials can provide opportunities for resource recovery, but they also introduce challenges involving fine particles, low concentrations and large impurity loads. The relevant question is not only whether REEs can be recovered experimentally, but whether the selected route reduces the quantity of material requiring chemical treatment while preserving useful elements and controlling the composition of residues and effluents (Peelman et al.; Abaka-Wood et al., “Recovery, Part 1”).

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Brazil provides a useful setting for this discussion because its resources include alkaline-carbonatite complexes, heavy-mineral occurrences and weathered deposits. The Geological Survey of Brazil's 2025 overview documents this diversity, including resources in Goiás and Minas Gerais and the Pela Ema operation in Minaçu. Such geological potential should be distinguished from demonstrated capacity to produce individually separated oxides. Mineralogical studies and hydrometallurgical investigations are needed to establish how different Brazilian feedstocks can enter an integrated processing chain (Cunha et al.).

This review aims to explain the fundamental characteristics of REEs, examine their principal mineral resources and critically discuss the technologies used for beneficiation, extraction, separation and recovery. Emphasis is placed on the relationship between mineral occurrence and process selection, the interpretation of published performance data, and the environmental and technological constraints relevant to route development. The discussion progresses from elemental properties to mineral resources and processing operations, incorporating Brazilian examples without limiting the analysis to a single deposit type.

2. Literature Review Methodology

This narrative review used targeted web searches to locate scientific publications and official geological information. The last bibliographic search was conducted on November 3, 2026. Sources consulted included publisher pages from ScienceDirect, Springer Nature, MDPI and the American Chemical Society; PubMed records; institutional repositories; and publications of the Geological Survey of Brazil and the United States Geological Survey. Crossref records were used to check titles, authorship, publication details and digital object identifiers. Search combinations included “rare earth” with “beneficiation,” “monazite flotation,” “xenotime,” “gravity separation,” “magnetic separation,” “ion-adsorption clay,” “ammonium sulfate,” “magnesium sulfate,” “acid baking,” “solvent extraction,” “ion exchange,” “precipitation,” “Brazil” and “environmental impacts.” Selection emphasized relevance to mineral resources and processing, identifiable feed

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characteristics, an interpretable experimental or process-development basis, and verifiable publication information. Foundational studies were retained alongside recent research.

The synthesis was thematic and qualitative. Experimental results, simulation outputs, field demonstrations and review-based descriptions were distinguished. Grades, recoveries and extraction percentages were retained on their reported basis and were not pooled across dissimilar materials. Geological resource information was used for context, with dates preserved. The review did not employ a systematic-review protocol, exhaustive database screening, meta-analysis or bibliometric analysis; its purpose was to connect representative evidence across the mineral-processing chain. Representative studies were discussed according to resource type and processing stage. Comparisons considered, when reported, feed characteristics, experimental scale, operating conditions, quantitative results and final products. The targeted, non-exhaustive search and differences in source accessibility and reporting detail represent limitations of this review.

3. Rare Earth Elements: Characteristics and Applications

The REE group comprises the fifteen lanthanides-lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium-together with scandium and yttrium. The name does not mean that every member is exceptionally scarce in the Earth's crust. The difficulty often lies in finding sufficiently concentrated, accessible and processable occurrences. Promethium has no stable isotope and is not a normal target of commercial mineral beneficiation. Yttrium commonly accompanies the heavier lanthanides because of its similar ionic dimensions, whereas scandium frequently follows different mineralogical and processing pathways (Balaram).

Lanthanides are commonly trivalent in aqueous processing systems. Across the series, increasing nuclear charge is accompanied by a gradual decrease in ionic radius, usually termed the lanthanide contraction. Their similar charge and ionic

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dimensions explain both their association in minerals and the difficulty of separating neighboring elements in solution. Small differences in hydration, complex formation and affinity for organic ligands can be exploited, but they generally require controlled solution chemistry and repeated separation stages. Physical beneficiation enriches the carrier minerals and cannot, by itself, resolve this chemical similarity (Xie et al.).

The conventional distinction between light and heavy REEs is useful but not entirely uniform. In this review, light REEs refer to La through Eu, and heavy REEs to Gd through Lu together with Y; Pm is included in the chemical sequence but has no relevant natural ore inventory. Some publications place Gd with the light elements or distinguish an intermediate group. Sc is discussed separately when its behavior is relevant. Consequently, a published light- or heavy-REE recovery should be interpreted using the element list adopted by that study. Reporting Nd, Pr, Dy, Tb and Y separately is often more informative than relying exclusively on broad group totals (Goodenough et al.; Foley and Ayuso).

Electronic structure accounts for the contrast between similarity in much of their solution chemistry and diversity in their functional properties. Shielded 4f electronic states contribute to characteristic optical transitions and magnetic behavior. These properties are expressed in compounds and alloys whose performance also depends on crystal structure, composition and processing history. It is therefore insufficient to describe all REEs as interchangeable inputs to advanced technologies. The practical specification can concern the purity of an individual oxide, the composition of a mixed product, or the concentration of a trace contaminant that disrupts subsequent manufacturing (Balaram).

Permanent magnets provide a direct connection between elemental distribution and process objectives. Nd and Pr are central to widely used rare earth–iron–boron magnets, while Dy or Tb can be incorporated where greater resistance to demagnetization at elevated temperature is required. Sm–Co magnets serve other demanding applications. These uses explain why a concentrate dominated by abundant light REEs may still require detailed evaluation of the smaller fractions containing magnet-related elements. Recovering more total REE mass is not

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automatically equivalent to recovering a more useful product distribution. Mixed Nd–Pr products may be acceptable for some downstream routes, whereas other applications require individual-element separation (Goodenough et al.).

Catalytic applications frequently involve La and Ce. The accessibility of both trivalent and tetravalent cerium is especially important because it enables redox behavior that differs from the predominantly trivalent chemistry of most lanthanides. This distinction also influences extraction. Thermal or chemical treatment that stabilizes Ce(IV) can change its solubility and redirect it to a residue while other REEs enter solution. Such a residue may be an intended cerium product or an unwanted loss, depending on the flowsheet. The desired product slate must therefore be established before interpreting a reduced dissolved-cerium fraction as poor performance (Demol et al.; Ortiz-Castillo et al.).

For process evaluation, elemental assays must be distinguished from oxide-equivalent grades. Total rare earth oxides (TREO) represent a calculated sum using specified oxide forms, whereas total rare earth elements (TREE) represent elemental mass. Neither is identical to the mass fraction of REE-bearing minerals. A concentrate containing monazite also contains phosphate and may include substituent elements; its mineral percentage cannot be compared directly with its TREO grade. Similarly, a solution analysis in milligrams per liter becomes an extraction result only after accounting for liquid volume and the corresponding inventory in the feed. These distinctions are essential when comparing physical concentration, leaching and product precipitation (Bazin and Boulanger; Battsengel et al., “Magnetic Separation”).

4. Mineral Resources and Geological Occurrence

The geological setting establishes the likely mineral assemblage, but process selection requires a more detailed description of where each element occurs. Carbonatites and associated alkaline complexes, peralkaline igneous systems, heavy-mineral sands and weathering profiles are important resource settings. They can contain different REE minerals within the same deposit, and their chemical

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compositions may vary between geological domains. Foley and Ayuso describe this diversity of conventional deposit types and the variable distribution of lighter and heavier REEs. For processing, the decisive distinction is between a discrete mineral that can potentially be liberated and concentrated, an element dispersed within another mineral, and an ion accessible at a mineral–water interface (Foley and Ayuso).

Bastnaesite is a fluorocarbonate commonly represented by the simplified formula $REECO_3F$. Natural compositions are variable and frequently enriched in light REEs. Its association with carbonate gangue can create flotation difficulties because collector interactions are affected by dissolved calcium, carbonate chemistry and the availability of surface metal sites. Fluorine also remains relevant after concentration: decomposition must account for its distribution among gas, solution and solid products. A high-grade bastnaesite concentrate can reduce the mass requiring chemical treatment, but it does not remove the need to manage the non-REE constituents intrinsic to the mineral (Jordens et al., “A Review”; He et al.).

Monazite is a phosphate, simplified as $REEPO_4$, commonly dominated by light REEs. It occurs in igneous and metamorphic rocks, weathered deposits and heavy-mineral accumulations. Substitution allows variable incorporation of Th and U, but their concentrations must be measured for the specific material. Its phosphate framework influences the severity of chemical opening, while grain size and association determine whether gravity, magnetic or flotation methods can produce a useful concentrate. A monazite-bearing placer and an ultrafine carbonatite-related material may therefore require substantially different front-end operations (Demol et al.; Mano et al.).

Xenotime is commonly represented by YPO_4, with heavier lanthanides substituting for Y. Its occurrence in heavy-mineral assemblages and evolved igneous systems makes it relevant to supplies with a different elemental distribution from many bastnaesite and monazite concentrates. Concentration can be hindered by associated dense minerals, including zircon and titanium-bearing phases, whose physical properties partly overlap those of the valuable mineral. The study of a xenotime preconcentrate from Pitinga, Brazil, by Pereira and Peres exemplifies the

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need for further selective treatment after an initial physical concentration stage. Xenotime-bearing material is consequently a distinct processing case, not simply a heavy-REE version of a bastnaesite ore (Pereira and Peres).

Apatite can incorporate REEs in its structure and may coexist with separate REE phosphates. Its potential recovery routes intersect with iron-ore and phosphate processing, depending on the host deposit. Recovering an apatite-rich fraction can remove iron-bearing minerals, but subsequent acid treatment may generate calcium-rich solutions or solids and distribute REEs between process streams. This creates opportunities for coproduct recovery and corresponding constraints on separation. The chemical value of the phosphate fraction, the destination of calcium and the occurrence of REEs within or outside apatite all affect the appropriate flowsheet (Battsengel et al., “Recovery of Light and Heavy”; Battsengel et al., “Magnetic Separation”).

Other hosts include allanite and related silicates, eudialyte-group minerals, and complex oxide minerals such as loparite. Some occur in alkaline or peralkaline rocks with multiple potential products. Their processing cannot be inferred only from total REE content because the host lattice and associated elements change decomposition chemistry. Eudialyte illustrates this point: acid dissolution can release REEs but also produce silica-related problems that compromise solid–liquid separation. The pretreatment investigated by Davris et al. was intended to control this behavior, showing that accessibility to acid does not necessarily translate into a readily filterable process slurry (Davris et al.).

Weathering modifies primary assemblages through dissolution, redistribution and secondary mineral formation. A weathered profile may contain resistant monazite or xenotime, newly formed phosphates, iron oxyhydroxides and clay minerals. REEs can be retained in several of these components. Their concentration in a regolith horizon can therefore reflect both residual enrichment of resistant particles and adsorption of ions released from less stable minerals. A high bulk assay in a clay-rich sample does not establish the proportion accessible to salt leaching. Identifying that proportion is an analytical and metallurgical task, not a conclusion that follows from the geological name of the deposit (Borst et al.;

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Cunningham et al.).

Ion-adsorption resources are distinguished by an appreciable exchangeable REE inventory associated with mineral surfaces. Kaolinite and halloysite are common components, although the clay assemblage and contributions from other phases vary. Borst et al. used spectroscopic evidence to investigate the coordination environments of REEs in natural regolith-hosted deposits. Their work provides a structural basis for evaluating the relatively weakly bound fraction targeted by ion-exchange leaching. Adsorption is nevertheless not a single universal state: the nature of the surface complex affects how readily an ion is released when the surrounding solution changes (Borst et al.).

Experiments on individual clay minerals reinforce this distinction. Bishop et al. found that clay type, pH and ionic strength affected REE adsorption, with lower adsorption under acidic conditions and at higher ionic strength. Illite and kaolinite did not exhibit identical capacities, and spectroscopic modeling indicated both inner- and outer-sphere environments. These observations caution against assigning a single exchange capacity or leaching response to all clay-rich ores. They also explain why mineralogical identification should be combined with selective extraction and solution analysis when evaluating a natural sample (Bishop et al.).

Ding and Azimi separated a South American clay into fractions below 0.25 mm, from 0.25 to 0.5 mm, and from 0.5 to 2 mm. The corresponding physisorbed REE fractions were 31%, 40% and 24%, while mineralized fractions were 61%, 55% and 71%. These reported categories do not sum to 100% and should therefore not be interpreted as a complete distribution of the REE inventory. Thus, the finest fraction did not have the highest proportion of readily exchangeable REEs. These are operationally determined fractions for the studied material, not universal proportions for ion-adsorption deposits. Their importance is that particle-size enrichment and chemical accessibility did not follow the same trend (Ding and Azimi).

Cunningham et al. subsequently reported detailed characterization of a South American granitic regolith using complementary diffraction, microscopic, surface and microanalytical methods. The coexistence of monazite and ion-adsorbing clays

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required consideration of both mineral-bound and surface-associated inventories. For route development, the study supports separate assessment of what saline desorption can recover and what would require more intensive treatment of the remaining solids. Combining these inventories into one nominal recovery target could obscure the reagent and residue costs of accessing the second fraction (Cunningham et al.).

Brazilian examples also show the importance of textural information. Mano et al. investigated two monazite-bearing samples from Catalão, Goiás, using chemical and mineralogical methods. Their results indicated monazite liberation below 75 μm in the lower-grade sample and below 150 μm in the higher-grade sample, despite the occurrence of very fine monazite grains. The distinction between mineral grain size, particle size and aggregation is important when interpreting these observations. The reported potential for size-based rejection of barite and quartz is a basis for concentration tests (Mano et al.).

The 2025 Geological Survey of Brazil overview identifies resources and projects in several geological settings, including Catalão, Araxá, Tapira, Poços de Caldas and Minaçu. The entries describe different commodities and development stages; an operating phosphate or niobium mine that contains REEs is not necessarily an operating REE separation plant. In the case of weathered resources, demonstration of exchangeable inventory is required alongside geological delineation. This distinction is especially relevant when comparing national geological potential with the smaller set of projects that have established a processing route and a marketable product (Cunha et al.).

Table 1 summarizes the principal mineral hosts and resource classes discussed here. The simplified formulas describe representative compositions, not fixed assays for natural ores. The comparison emphasizes the consequences of occurrence mode for concentration and extraction, including cases in which the valuable elements are dispersed through surfaces or host minerals and are not contained in readily separable grains.

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Table 1. Principal REE-bearing minerals and resource classes, with implications for processing. Formulas are simplified; natural compositions and REE distributions vary.

Host or resource	**Composition and occurrence**	**Processing implications**	**Sources**
Bastnaesite	$REECO_3F$; commonly LREE-rich; carbonatite and related systems	Liberation and flotation; decomposition must account for fluoride and Ce oxidation state	(Jordens et al., "A Review"; He et al.)
Monazite	$REEPO_4$; commonly LREE-rich; igneous, weathered and placer resources	Gravity, magnetic separation or flotation where liberated; phosphate opening and measured Th/U control	(Mano et al.; Demol et al.)
Xenotime	YPO_4 with HREE substitution; evolved igneous rocks and heavy-mineral assemblages	Concentration from other dense minerals; phosphate decomposition	(Pereira and Peres; Foley and Ayuso)
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$; REEs may substitute in the lattice or occur in associated phases	Integration with iron/phosphate processing; Ca and P distributions affect extraction	(Battsengel et al., "Recovery of Light and Heavy"; Battsengel et al., "Magnetic Separation")
Complex silicate and oxide hosts	Eudialyte, allanite, loparite and related minerals; alkaline/peralkaline systems	Host-specific decomposition; silica and other major components can control separation	(Davris et al.; Foley and Ayuso)
Ion-adsorption regolith	No single ore-mineral formula; exchangeable REEs coexist with other hosting modes	Quantify exchangeable inventory; salt desorption; mineral-bound fraction requires separate assessment	(Borst et al.; Ding and Azimi)

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Tailings and mine waters	Composition depends on original ore and preceding treatment	Selective reprocessing or solution recovery; impurity loading and coproducts matter	(Peelman et al.; Roa et al.)

5. Beneficiation of Rare Earth-Bearing Ores

Beneficiation aims to increase the concentration of valuable mineral carriers while rejecting gangue before more intensive extraction. Its benefit depends on both the amount of unwanted material removed and the REE inventory retained. A small, high-grade concentrate may be unsuitable if it excludes a large share of Nd, Pr or the targeted heavy REEs. Conversely, a moderate-grade preconcentrate can be useful if it removes acid-consuming or filtration-limiting gangue. The downstream requirements therefore help define the appropriate grade–recovery compromise. Physical concentration should be evaluated as part of the route, with separate balances for the valuable elements and the impurities that influence later treatment (Jordens et al., “A Review”; Battsengel et al., “Magnetic Separation”).

Characterization should precede selection of equipment. Bulk assays identify the elemental inventory, diffraction identifies sufficiently abundant crystalline phases, and microscopy provides information on associations and textures. Automated mineralogy can estimate liberation and mineral distributions across size fractions, although resolution and classification errors become increasingly important for very fine or compositionally complex phases. The characterization of Nechalacho separation products by Jordens et al. illustrates the value of examining actual products: a mineral's nominal density or susceptibility does not fully describe the behavior of a composite particle containing that mineral (Jordens et al., “Beneficiation, Part 2”).

Crushing and grinding expose valuable grains and create particles that can respond selectively to separation forces. The required size depends on the texture of the ore, not on a universal REE processing target. Insufficient grinding retains valuable minerals in gangue-rich composites, whereas excessive grinding creates fines that are difficult to recover by gravity and can be entrained during flotation. In an ore containing several REE hosts, one mineral can become liberated while another remains locked. A size-by-size mineral balance is therefore preferable to

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selecting a grind solely from the bulk particle-size distribution (Jordens et al., “Beneficiation, Part 1”; Bazin and Boulanger).

Bazin and Boulanger investigated a carbonate-rich Canadian ore containing bastnaesite and monazite with a fine mineral grain size. Their laboratory preparation produced a ground material with a d80 of 45 µm. The study showed slower flotation and lower recovery of monazite than of bastnaesite, despite both contributing to the REE assay. A circuit simulation calibrated from batch tests predicted a concentrate exceeding 40% TREO after two cleaning stages. This is a modeled circuit result, not evidence of sustained operation at pilot or industrial scale (Bazin and Boulanger).

Desliming presents a more difficult choice. Removing fine gangue can improve pulp rheology, reduce collector consumption and limit entrainment, but REE minerals may themselves be concentrated in the fine fraction. Abaka-Wood et al. investigated an Australian saprolite containing 1.14% TREO. With desliming, sodium oleate and starch/sodium silicate depressants, concentrates reached 5.87% TREO at 45% recovery at pH 9 and 4.22% TREO at 50% recovery at pH 10.5. These results show a grade–recovery tradeoff and should retain the study's feed and recovery basis when assessing the contribution of desliming (Abaka-Wood et al., “Recovery of Rare Earth Elements Minerals in Complex”).

Gravity concentration exploits differences in particle motion arising from density, size and shape in a fluid or flowing bed. Dense REE minerals can be enriched relative to quartz and feldspar using shaking tables, spirals or centrifugal concentrators, where particle sizes and liberation are suitable. The method is attractive for rejecting a large mass of low-density gangue without requiring selective adsorption of reagents. Its limitations are equally important: dense iron oxides and other heavy minerals can accompany the product, and very fine particles experience strong fluid-drag effects that diminish density selectivity (Abaka-Wood et al., “A Study of the Feasibility”).

The Nechalacho investigations provide an example of gravity concentration as one component of a combined route. Jordens et al. examined a feed containing low-density diamagnetic silicates and dense iron oxides as well as REE minerals.

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Knelson concentration and low-intensity magnetic separation addressed different gangue populations. The experimental work demonstrated why a dense product may require magnetic cleaning before flotation. The authors explicitly distinguished their test sequence from the selected commercial design for the deposit; its role here is to illustrate process logic, not to describe the current operating plant (Jordens et al., “Beneficiation, Part 1”).

Magnetic separation can recover a paramagnetic REE-bearing fraction or reject a magnetic gangue fraction. The objective depends on mineral properties and associations. Low-intensity devices can remove strongly magnetic iron minerals, whereas high-intensity or high-gradient devices are used for more weakly magnetic particles. Field strength alone does not determine performance; field gradient, matrix geometry, flow conditions and particle size also affect capture. Composite particles and mechanical entrapment can transfer nominally nonmagnetic material into the magnetic product. Consequently, reporting only a separator setting and concentrate assay is insufficient to explain selectivity (Jordens et al., “A Review”; Abaka-Wood et al., “Recovery, Part 1”).

In the iron-oxide-silicate tailings investigated by Abaka-Wood et al., the feed contained 1.07% TREO and 26.2% Fe. Magnetic treatment achieved only modest REE preconcentration and required complementary downstream processing. This outcome is consistent with overlapping responses of valuable particles and iron-rich gangue. It also illustrates why removal of iron is not necessarily equivalent to recovery of REEs: depending on their associations, valuable minerals may accompany either stream. Both magnetic and nonmagnetic products require mineralogical and chemical assessment (Abaka-Wood et al., “Recovery, Part 1”).

A different outcome was obtained for the apatite-iron ore studied by Battsengel et al. Wet high-intensity separation directed 71% of the iron to the magnetic fraction while retaining 92% of the REEs in the nonmagnetic material. Subsequent dilute sulfuric acid treatment dissolved more than 85% of the REEs from that fraction. These percentages describe successive stages. The leach extraction must not be reported as the recovery from the original ore, and neither value includes all subsequent purification losses. The example demonstrates an

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appropriate magnetic-rejection function when REEs and iron occupy sufficiently different mineral populations (Battsengel et al., “Magnetic Separation”).

Electrostatic separation is particularly relevant to suitably sized, dry heavy-mineral assemblages. It uses differences in electrical behavior and can complement gravity and magnetic stages when several dense minerals occur together. Moisture, coatings and particle-size spread influence the separation response. It is therefore more readily considered for prepared heavy-mineral concentrates than for wet ultrafine pulps. The broader review by Jordens, Cheng and Waters includes electrostatic separation among established REE beneficiation options (Jordens et al., “A Review”).

Flotation is important where fine mineral liberation makes density-based concentration difficult or where other physical properties provide insufficient contrast. Collectors promote attachment of selected particles to bubbles, while depressants and modifiers influence gangue recovery and solution chemistry. Fatty acids and hydroxamate reagents are widely investigated for REE-bearing minerals. Their usefulness depends on adsorption at the actual mineral surfaces, including alteration layers, dissolved species and competing gangue. A collector that gives high recovery in a single-mineral test can still provide poor concentrate quality when used on a carbonate-rich ore (Zhang et al.)

Zhang and Honaker subsequently combined octanohydroxamic acid, sodium silicate and EDTA in a model monazite–calcite system. At 2.5×10^{-4} mol/L collector, 0.05 g/L sodium silicate and 6×10^{-5} mol/L EDTA, monazite recovery exceeded 90%, while calcite recovery was approximately 20%. These results demonstrate selective control under the tested microflotation conditions. They do not establish a commercial concentrate grade for a natural ore. The contribution is mechanistic: managing soluble calcium and depressant interactions can improve discrimination between minerals with competing surface responses (Zhang and Honaker).

For xenotime, Pereira and Peres investigated flotation of a Pitinga preconcentrate. The case demonstrates the relevance of selective flotation after heavy-mineral concentration and extends the discussion beyond predominantly light-REE ores. Differences in the associated minerals and the proportion of Y-

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bearing phosphate change the separation problem. Monazite and xenotime should not be assigned identical flotation conditions merely because both are phosphates. Their surface compositions, impurities and gangue interactions must be evaluated under the conditions of the actual processing water (Pereira and Peres; Zhang and Honaker).

Ion-adsorption clays require a separate assessment. If the target REEs are held on widely distributed mineral surfaces, there may be no discrete valuable grain to recover by gravity or flotation. Screening, disaggregation or removal of barren coarse particles can still be useful, but their effect should be measured as accessible REE retained per unit mass treated. The size-dependent fractions reported by Ding and Azimi show why total grade alone is insufficient. Rejecting a low-grade size fraction can be unfavorable if it contains a substantial share of the readily exchangeable inventory (Ding and Azimi).

The feed specification for hydrometallurgy should therefore include more than a minimum REE grade. Relevant properties include mineral hosts, acid-neutralizing gangue, Fe and Al content, phosphate and fluoride inventory, radionuclide distribution, particle size and solid–liquid separation behavior. A concentrate that is easy to produce may still be expensive to open or purify. Conversely, selective removal of a troublesome gangue phase can have value even when the increase in TREO grade is modest. Beneficiation development is most informative when the resulting products are actually tested in the intended chemical route, so that improvements in one operation can be checked against consequences in the next.

6. Extraction and Recovery of Rare Earth Elements

Chemical extraction begins where physical concentration can no longer separate the desired elements from their hosts. Mineral opening disrupts a resistant lattice or transforms it into more soluble compounds; leaching transfers REEs into a liquid phase; purification removes unwanted constituents; and recovery produces a compound, oxide or other specified product. These functions can overlap within an integrated operation, but they remain distinct when interpreting performance. A

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mixed REE carbonate or oxide can be a saleable intermediate while still requiring separation into individual elements elsewhere. The appropriate endpoint depends on the intended downstream use (Demol et al.; Ortiz-Castillo et al.).

For refractory phosphate minerals, sulfuric acid baking followed by water leaching is an established route family. The bake transforms mineral constituents under conditions that differ from ordinary dilute-acid leaching. REE sulfates formed during digestion are subsequently dissolved during the water-leach stage. Demol et al. compare the effects of feed mineralogy, temperature, duration, acid-to-solid ratio and particle size across several ores and concentrates. Their synthesis shows that these variables influence both REE accessibility and the behavior of phosphate, thorium and other constituents; a single preferred bake temperature cannot be transferred across mineral systems (Demol et al.).

Acid dosage must be considered against the complete reactive mineral inventory. Carbonates consume acid before or alongside the target mineral, while iron- and aluminum-bearing phases can increase dissolved impurity concentrations. A higher acid addition may improve extraction but can also increase neutralization demand and the quantity of salts generated later. The effect of beneficiation is therefore chemical as well as physical: removing reactive gangue changes the acid balance. Testing a purified mineral can identify decomposition mechanisms, but an ore or concentrate test is needed to determine the practical reagent requirement (Battsengel et al., “Recovery of Light and Heavy”; Ortiz-Castillo et al.).

Alkaline opening provides another route for phosphate concentrates. Concentrated alkali treatment can convert REE phosphates to hydroxide-bearing solids while transferring phosphate into an alkaline stream, followed by washing and acid dissolution of the REE-bearing material. Its suitability depends on mineral composition, alkali consumption and the handling of phosphate and radionuclides. Acid and alkaline routes should be compared at equivalent product and waste boundaries. Evaluating only their opening efficiencies overlooks washing demand, neutralization, reagent regeneration and the composition of the resulting leach liquor (Demol et al.; Ortiz-Castillo et al.).

Bastnaesite processing introduces additional control over fluorine and cerium

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oxidation state. Thermal treatment can change the mineral's reactivity and the distribution of Ce between soluble and refractory products. He et al. investigated selective transformation under nitrogen followed by HCl/$AlCl_3$ leaching of a mixed bastnaesite–monazite concentrate. This approach uses differences in the minerals' chemical responses to separate them. It is an example of selective decomposition, not evidence that the same treatment will be optimal for every mixed concentrate. Thermal requirements, reagent recycling and fluoride management remain part of its assessment (He et al.).

Hydrochloric acid is useful in systems where chloride solutions suit subsequent recovery, while sulfuric acid can provide different solubility and precipitation behavior. Nitric acid also has a role in particular integrated routes. Peelman et al. investigated apatite-bearing mine tailings using nitric-acid leaching, calcium crystallization and solvent extraction, with the aim of recovering REEs alongside other products. Such a route is valuable because it accounts for major components of the host mineral. Its feasibility depends on recovering or managing those components, not simply on achieving a high REE concentration in an initial leachate (Peelman et al.).

Acid-reactive silicates can pose a different problem. Davris et al. used an acid-fuming pretreatment followed by water leaching to recover more than 90% of REEs from an eudialyte concentrate while suppressing silica-gel formation. The result demonstrates that sequencing the contact between acid, solid and water can be as important as the acid identity. Silica-rich gels can retain liquor, impede filtration and complicate washing. A leaching experiment should consequently report the recoverable liquid and residue behavior, since high dissolved concentrations in a small laboratory sample do not alone establish a workable solid–liquid separation (Davris et al.).

Ion-adsorption clays are processed through a different mechanism when the target inventory is exchangeable. Cations supplied by a salt solution compete with adsorbed REE ions, which are released into the aqueous phase without requiring complete dissolution of the clay structure. Moldoveanu and Papangelakis demonstrated recovery through ion exchange using sulfate and chloride salts under

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ambient conditions. The readily exchangeable fraction is the relevant target for this route. REEs contained in resistant monazite or other mineral lattices require separate treatment and should not be assumed to respond to the same salt solution (Moldoveanu and Papangelakis, “Recovery, I”).

Ammonium sulfate supplies ammonium ions for exchange and a sulfate-containing aqueous environment. In their subsequent study, Moldoveanu and Papangelakis reported 80 to 90% total REE extraction under favorable conditions around pH 3 to 4 and temperatures below 50 °C. Those values belong to the examined clays and test conditions. Their significance is the existence of a mild extraction window, not a universal operating prescription. Raising pH or temperature can change hydrolysis and precipitation behavior, so more intensive conditions do not necessarily increase the amount remaining in the recoverable solution (Moldoveanu and Papangelakis, “Recovery, II”).

The initial and final pH values both matter because contact with the ore can change solution acidity. Lower pH may promote desorption but can also mobilize Al or Fe from associated phases. At higher pH, hydrolysis, adsorption or precipitation can remove REEs from solution. Bishop et al.'s adsorption experiments show that changing acidity and ionic strength changes REE retention by clay minerals. For a natural ore, the net measured extraction combines release from the solid with any subsequent readsorption or precipitation. Analysis of both leachate and washed residue helps distinguish incomplete release from secondary loss (Bishop et al.; Liu et al.).

Liquid-to-solid ratio affects reagent availability, solution concentration and transport. Dilute slurries can provide more reagent per unit ore at a fixed molarity, but produce larger liquid volumes for downstream recovery. Higher solids contents reduce liquid volume but may worsen suspension, mixing and washing. These effects cannot be summarized by extraction percentage alone. Two conditions with similar extraction may yield substantially different REE concentrations and impurity-to-REE ratios. A meaningful comparison reports the dry solid mass, initial liquid volume, solution additions, wash volumes and the basis used to calculate recovery.

Contact time and agitation should also be interpreted in relation to the physical

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system. Stirring can reduce external transport limitations and prevent settling, but the same revolutions per minute in vessels of different size do not imply equivalent mixing. In a permeable ore body, flow pathways, diffusion, channeling and residence-time distribution can dominate solution access. Hu et al. examined magnesium-sulfate exchange kinetics using 80 g of ore with 400 mL of solution, concentrations of 0.1 to 0.3 mol/L, temperatures of 298 to 328 K and agitation at 100 rpm. Their results linked particle size to reaction rate, while showing concurrent aluminum release (Hu et al.).

Magnesium sulfate has received attention as an alternative to ammonium salts, but removal of nitrogen from the reagent does not eliminate every processing constraint. Magnesium must be managed in the circulating solution, and REE–Al selectivity remains important. Liu et al. studied a 0.15 mol/L magnesium-sulfate solution at initial pH 2 and found that increasing aluminum already present in the lixiviant reduced net aluminum leaching while changing REE leaching relatively little. This is relevant to recirculation because solution composition evolves during reuse. It does not establish that unlimited impurity accumulation is acceptable (Liu et al.).

Complexing agents can modify the extraction window by stabilizing dissolved species. Moldoveanu and Papangelakis investigated chelation-assisted leaching at ambient conditions using 50 g of clay, a liquid-to-solid ratio of 2 mL/g and 30 min contact. Selected ligands allowed extraction approaching that achieved with a higher ammonium concentration. The practical question is whether the reduction in salt demand exceeds the added cost and treatment burden of the ligand. Complexants can also affect impurity dissolution, resin loading, solvent extraction and precipitation, so their benefit should be followed through the downstream sequence (Moldoveanu and Papangelakis, “Chelation-Assisted”).

The coexistence of occurrence modes requires explicit accounting. In the South American clay investigated by Ding and Azimi, a large mineralized inventory remained outside the readily exchangeable fraction. Increasing salt concentration or leaching duration cannot be assumed to recover that material efficiently. A second treatment of the residue may be technically possible, but its incremental

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recovery must be assessed against new reagent use, dissolution of additional gangue and residue changes. The decision to pursue that fraction depends on its element distribution and accessibility, not only on the mass of REEs remaining (Ding and Azimi; Cunningham et al.).

Electrokinetic methods seek to improve access and transport by applying an electric field to the ore–solution system. Wang et al.'s initial work developed the concept for weathering-crust resources, followed by an industrial-scale investigation that addressed electrode reliability and leakage. The later study reported recovery above 95% during a 60-day field trial. This advances the evidence beyond stirred batch tests, but remains a demonstration under particular geological and hydrological conditions. Conductivity, electrode spacing, electricity demand and recovery of the mobilized solution must be considered before transferring the approach to another deposit (G. Wang et al., “A Green and Efficient”; G. Wang et al., “Industrial-Scale”).

After leaching, solid–liquid separation and washing determine how much dissolved REE is actually recovered. Fine clay particles, silica-rich material and precipitated impurity phases can impair clarification and retain valuable liquor. A laboratory extraction calculated from a filtered aliquot may overstate the amount recoverable in a dewatered plant product if substantial solution remains in the residue. Countercurrent washing can improve recovery with lower fresh-water demand, but also changes the volume and concentration of the combined liquor. The chemical and physical balances must therefore be considered together when comparing routes.

Impurity removal prepares the solution for selective REE recovery. Iron and aluminum may be removed by controlled hydrolysis or other precipitation steps, but precipitating solids can adsorb or occlude REEs. Calcium, phosphate, fluoride and sulfate can alter the composition and filterability of those solids. A treatment that gives a clear solution can still incur significant valuable-element loss. For this reason, impurity-removal tests should report both the residual impurity concentration and the REE inventory transferred to the precipitate. Roa et al.'s work on acidic mine water illustrates integration of competing-metal removal with

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subsequent resin-based separation (Roa et al.).

Solvent extraction transfers selected dissolved species between an aqueous phase and an immiscible organic phase containing an extractant. Loading, scrubbing and stripping perform different functions: loading recovers REEs into the organic phase, scrubbing removes co-extracted species, and stripping returns the desired inventory to a suitable aqueous product. Xie et al. review acidic organophosphorus, neutral and basic extractant systems and the influence of aqueous chemistry on their behavior. Because adjacent lanthanides have similar affinities, repeated countercurrent stages are commonly necessary to achieve high-purity separation. High loading in one contact is therefore not equivalent to effective separation of neighboring elements (Xie et al.).

The composition of the leachate influences solvent-extraction circuit complexity. Acidity affects the loading of acidic extractants, while anion composition and impurity concentrations affect speciation, phase behavior and selectivity. A highly dilute liquor may require preconcentration, and suspended particles can compromise phase disengagement. Product targets also matter: a mixed Nd–Pr stream has a different separation requirement from individually purified Nd and Pr. The 2026 review by Ortiz-Castillo, Dreisinger and Liu emphasizes coordination chemistry and the limitations of emerging alternatives, including reagent properties and incomplete demonstrations of recycling at scale (Ortiz-Castillo et al.).

Ion-exchange resins provide an alternative or complementary means of concentrating and fractionating REEs. A resin can load selected ions from a dilute solution and release them into a smaller volume of eluent, although competing ions consume capacity and alter breakthrough. Silva et al. examined drainage from a former Brazilian uranium mine containing 97 mg/L REEs at pH 3.5. Using a strong-acid cation resin and 0.01 mol/L ammonium-EDTA elution, they obtained approximately tenfold concentration and partial separation of light and heavy groups. Reported elution efficiencies of 90 to 100% refer to the loaded resin inventory, not necessarily to all REEs in the initial drainage (Silva et al.).

Souza et al. investigated the effects of pH, eluent concentration and column configuration on related resin fractionation. At initial pH 6.0 with 0.02 mol/L

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ammonium-EDTA, the early eluate over 0 to 10 bed volumes reached a reported heavy-REE fraction of 98.4%. This represents enrichment of a selected group in a particular cut. It should not be described as 98.4% recovery of all heavy REEs or as the purity of an individually separated oxide. Extending the collected volume can improve mass recovery while reducing the degree of fractionation, requiring an explicit purity–recovery compromise (Souza et al.).

Roa et al. used sequential ligand-impregnated and chelating resins to separate REE groups from Aznalcóllar acidic mine water. The feed contained 18.56 mg/L REEs together with much higher Al, Fe and Zn concentrations. Such a system demonstrates the importance of pretreatment and selective capacity in dilute resources. Resins can avoid treating the entire water volume through a large solvent-extraction circuit, but their regeneration produces another solution requiring processing. Adsorption capacity, cycle stability, eluent consumption and the concentration of the recovered fraction must all be included in route evaluation (Roa et al.).

Precipitation converts dissolved REEs into a recoverable solid, frequently as oxalates, carbonates or hydroxide-bearing products. It can recover a mixed product or follow individual-element separation. Nawab, Yang and Honaker investigated oxalic-acid precipitation from a chloride leachate containing significant contaminants. Raising pH from 0.5 to 2.5 increased precipitation efficiency from 0 to 98.9% under their tested conditions, while iron adversely affected performance. The finding demonstrates the importance of acid–base and competing-ion chemistry. It does not prescribe a universal pH for solutions with different REE concentrations, anions or impurities (Nawab et al.).

Product recovery also depends on crystal growth, filtration and washing. Very fine precipitates may be difficult to separate and can retain contaminated mother liquor. Increasing precipitant dose can increase recovery while raising consumption or impurity incorporation. Calcination of suitable precipitates produces oxide products, but does not itself separate a mixed lanthanide inventory into individual elements. The product should be characterized on a dry or calcined basis consistent with its specification, including non-REE impurities and residual volatile

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components. Metallic REE production requires further reduction or electrochemical operations beyond the oxide-recovery endpoint considered here (Nawab et al.; Battsengel et al., “Recovery of Light and Heavy”).

7. Environmental Challenges and Future Perspectives

Environmental performance varies with the resource, process chemistry and the boundary used for assessment. A hard-rock route with fine grinding and chemical opening has a different burden profile from a salt-leached regolith, while a secondary aqueous source already enters the chain in dissolved form. Zapp et al. discuss this variation across primary REE production systems. The relevant comparison must specify whether it ends at mineral concentrate, mixed oxide, individual oxide or metal. Comparing products at different stages can assign an apparent advantage to a route whose downstream processing has simply been excluded (Zapp et al.).

Reagent consumption is a major link between upstream selectivity and environmental burden. Unnecessary dissolution of carbonates, Fe or Al increases chemical inputs and the amount of neutralizing reagent required later. Beneficiation that rejects such phases can reduce these demands, but introduces its own energy, water and tailings requirements. The most useful optimization criterion is therefore not minimum acid concentration in isolation. It is the quantity of specified product obtained relative to the complete reagent, energy and residue inventory, with losses of valuable elements and redistribution of contaminants included (Schreiber et al.; Demol et al.).

Ammonium-based exchange leaching requires control of nitrogen-containing solutions and residual salts. Magnesium sulfate avoids introducing ammonium, but its use still generates saline process streams and can mobilize aluminum. Ying Wang et al.'s life-cycle comparison of the two routes used a field-based inventory and modeled production of individual oxides and elements In that modeled comparison, the magnesium sulfate route showed lower terrestrial ecotoxicity potential than the ammonium sulfate route, although the finding is specific to the

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assessed system and impact category (Y. Wang et al.).

Water recirculation reduces demand for fresh water only when the recycled solution remains suitable for processing. Dissolved calcium can affect flotation chemistry, while aluminum, sulfate and residual complexants can influence leaching and product recovery. Reuse may require selective treatment, a controlled purge or routing of different solution streams to different operations. Tests conducted exclusively with fresh deionized water may therefore fail to predict stable plant operation. The calcium effects demonstrated in monazite flotation and the influence of aluminum already present in magnesium-sulfate lixiviant provide concrete reasons to include recycled-water chemistry in development programs (Zhang et al.; Liu et al.).

Tailings and chemical residues also need distinct descriptions. A physical separation reject can retain valuable minerals and naturally occurring radionuclides without having undergone extensive dissolution. A leach residue may contain transformed minerals, precipitated salts and entrained acidic or saline liquor. Their storage, drainage behavior and potential for further recovery differ. Reprocessing can reduce the amount of a valuable component left in a waste stream, but does not automatically reduce its total environmental burden. A new chemical treatment may mobilize constituents that were previously retained in relatively stable mineral phases (Zapp et al.; Peelman et al.).

Thorium and uranium management should be based on measured mineral and stream distributions. Some monazite-bearing concentrates can enrich these elements during beneficiation, while decomposition changes their solubility and association with residues. Other resources may have much lower radionuclide inventories. Treating every REE deposit as equally radioactive is scientifically inappropriate, but ignoring these components because they are not the target product is equally inadequate. Mineralogical identification, chemical assays and process mass balances are needed to determine whether radionuclides remain in a solid, enter solution, or become concentrated during impurity removal (Demol et al.; Zapp et al.).

Scaling introduces constraints that are weakly represented in short batch

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tests. Ore variability changes reagent demand, fine particles affect mixing and filtration, and recirculation introduces time-dependent chemistry. Continuous pilot operation can reveal accumulation, fouling, phase-disengagement problems and reagent losses that do not appear during a single experiment. Schreiber, Marx and Zapp's review of life-cycle studies also shows that inconsistent inventories and boundaries can produce misleading environmental comparisons. More transparent reporting of water balance, reagent make-up, solids handling and product specifications would improve both engineering assessment and comparison between studies (Schreiber et al.).

Electrokinetic extraction is a useful example of progress from mechanistic research toward field testing. The studies by Gaofeng Wang and colleagues move beyond demonstrating desorption in a mixed slurry and address transport within a porous ore body. The later trial provides evidence of engineering development, including electrode and leakage control. Future evaluation should examine spatial variability, electrical consumption per unit product, collection efficiency of the mobilized solution and performance over repeated or extended campaigns. A successful field demonstration is stronger evidence than a laboratory test, but it does not eliminate the need for site-specific verification (G. Wang et al., “A Green and Efficient”; G. Wang et al., “Industrial-Scale”).

For low-grade ores and mine tailings, the key development opportunity is selective treatment of the fraction that controls process cost. This may involve rejecting a large mass of barren material, recovering a coproduct, or targeting a chemically accessible inventory while retaining refractory material for a separate assessment. The limited magnetic upgrading of the South Australian tailings and the more selective iron rejection from apatite ore illustrate why the same equipment can provide different benefits. Work on apatite-bearing tailings further indicates that recovery of phosphorus and calcium products may alter the evaluation of an REE route (Abaka-Wood et al., “Recovery, Part 1”; Battsengel et al., “Magnetic Separation”; Peelman et al.).

Brazilian opportunities should be framed around this diversity. Carbonatite-related monazite requires attention to ultrafine mineral associations and

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concentration selectivity; weathered resources require quantification of exchangeable inventory and control of saline solutions; and mining-related waters can support recovery methods based on dilute-solution chemistry. The Catalão characterization and Brazilian resin studies show complementary needs in mineralogy and hydrometallurgy. Collaboration between geological characterization, beneficiation testing and solution-process development can help avoid a route being optimized for an unrepresentative sample or an incompletely defined product (Mano et al.; Silva et al.; Souza et al.).

8. Conclusions

Rare earth processing is governed by the combination of elemental distribution, mineral hosting and product requirements. Similar aqueous chemistry makes separation of neighboring lanthanides demanding, while differences among mineral hosts create distinct requirements for liberation and chemical extraction. Total REE or oxide-equivalent grade is therefore insufficient to select a route or judge its performance.

For ores containing discrete REE minerals, gravity concentration, magnetic separation and flotation can reduce the mass and impurity burden entering hydrometallurgy. Their effectiveness depends on liberation, particle size and the response of associated gangue. Published comparisons show that favorable single-mineral flotation behavior does not establish natural-ore selectivity, and a high-grade product can involve a substantial recovery penalty. Beneficiation should be assessed using element-specific balances and tests on the resulting chemical-treatment feed.

Ion-adsorption clays require a different starting assessment. Exchangeable and mineral-bound inventories can coexist, and particle-size enrichment does not necessarily increase the exchangeable proportion. Saline desorption is appropriate to the accessible fraction; aggressive treatment of the residual inventory is a separate decision with additional reagent, impurity and residue consequences. Operating conditions must be validated for each material and for the intended slurry,

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column or field configuration.

Acid or alkaline opening, leaching, impurity removal, solvent extraction, resin treatment and precipitation perform different functions. Extraction from a solid, elution from a resin and precipitation from a liquor have different denominators and cannot be treated as equivalent recoveries. Mixed REE products should also be distinguished from individually purified oxides.

Environmental improvements require integration of reagent and water balances, impurity selectivity, residue behavior and radionuclide management where relevant. The diversity of Brazilian resources offers several development paths, but each requires mineralogical and metallurgical evidence at an appropriate scale. The most transferable basis for progress is a transparent connection between occurrence mode, separation mechanism, feed-to-product recovery and the composition of all major process streams.

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