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Particle Size, Morphology, Texture, and Liberation Characteristics of Rare Earth-Bearing Phases in Phosphogypsum: Consequences for Beneficiation and Process Design

Antonio Clareti Pereira, PhD
PhD in Chemical Engineering
University of São Paulo (USP)
Belo Horizonte, Minas Gerais, Brazil
E-mail: claretipereira@gmail.com
ORCID: https://orcid.org/0000-0001-8115-4279

Abstract

Phosphogypsum (PG) contains rare earth elements (REEs), but bulk concentration does not establish whether physical beneficiation is feasible. This critical review examines how gypsum crystallization, particle-size distributions, crystal habit, aggregation, mineral inclusions, and phase liberation affect REE deportment and the selectivity of downstream processing. Evidence from phosphogypsum studies is distinguished from methodological analogs in mineral processing, and the limitations of laser diffraction, sieving, sedimentation, automated mineralogy, and image-based textural analyses are evaluated. The synthesis shows that the critical design variable is not progressively finer particle size but the mass-balanced distribution of REE-bearing associations across size classes and their actual separability. Controlled comminution and dispersion can improve accessibility of discrete inclusions, yet may generate fines and worsen classification, flotation, filtration, and overall recovery. A staged characterization framework is proposed that links representative sampling, complementary sizing, size-specific chemical assays, quantitative mineralogy, breakage response, and closed process balances to evidence-gated flowsheet selection. The review identifies phase-resolved and size-resolved recovery measurements as a central research requirement for reliable beneficiation and process scale-up.

Keywords: Phosphogypsum; Rare earth elements; Particle size distribution; Mineral liberation; Automated mineralogy; Physical beneficiation

Highlights

- Bulk REE grade alone cannot establish phosphogypsum beneficiation potential.
- Crystal habit, inclusions, and aggregation jointly influence measured particle size.
- Liberation gains must be balanced against slimes generation and downstream selectivity.
- A mass-balanced, size-resolved mineralogical framework guides process selection.

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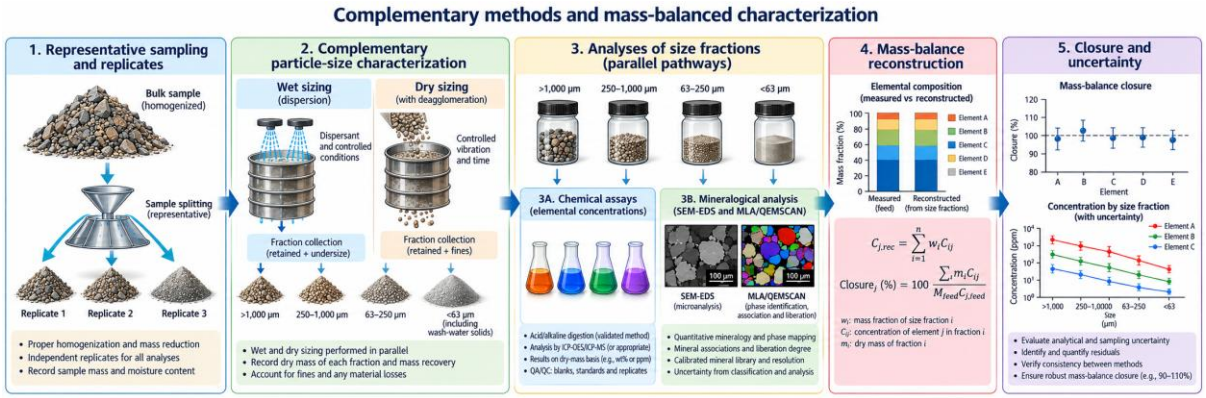
Graphical Abstract



1. Introduction

Phosphogypsum (PG), the calcium sulfate-rich residue generated during wet-process phosphoric acid production, is increasingly considered a secondary source of rare earth elements (REEs). However, its value cannot be inferred from bulk REE concentration alone. The physical accessibility of REE-bearing phases, their intimate association with gypsum, their distribution among crystal surfaces and inclusions, and the tendency of small particles to aggregate jointly govern whether beneficiation can create an economically meaningful preconcentrate. (Abdel-Aal et al., 2024; Chen et al., 2024; Dong et al., 2024)

Existing research has established multiple routes for leaching, purification, and valorization of PG, yet the translation from bulk characterization to liberation-controlled separation remains uneven. Smaller particle sizes or improved gypsum purity are not, by themselves, proof of REE liberation or enrichment. Equally, high leach extraction from untreated material does not demonstrate that additional grinding or classification would improve an integrated process. (Du et al., 2025; Guan et al., 2022a; Guan et al., 2023)

This critical review asks under which mineralogical and particle-size conditions physical preconcentration of REE-bearing phases in PG is technically defensible. It integrates evidence on crystal formation, particle size measurement, aggregation, mineral inclusions, image-based liberation analysis, controlled grinding, fraction-wise deportment, and downstream separation. Figure 1 provides the mechanistic frame, Table 1 distinguishes the

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different evidence classes, and Figure 4 develops the proposed decision sequence. (Huang et al., 2026; Kakar et al., 2026; Kakar et al., 2025)

The novelty relative to recent reviews of PG pretreatment and resource recovery is not the cataloguing of available leaching routes. It is the evidence-gated link between particle-size measurement, morphology, mineral association, size-resolved REE inventory, quantified liberation, and demonstrated selective partitioning before any physical beneficiation step is selected (Nkabinde et al., 2026; Shao et al., 2026; Hu et al., 2026).

Literature identification used section-specific Google Scholar searches, emphasizing 2020–2026 and extending to 2010–2026 where foundational or methodologically indispensable studies were needed. The final literature update for this revision was 6 November 2026. Representative query blocks were: ("phosphogypsum" AND ("rare earth" OR REE) AND ("particle size" OR morphology OR liberation)); ("phosphogypsum" AND ("rare earth" OR REE) AND ("pretreatment" OR grinding OR ultrasonication)); ("phosphogypsum" AND ("mineralogy" OR "SEM-EDS" OR "automated mineralogy")); ("phosphogypsum" AND (classification OR desliming OR flotation) AND (recovery OR deportment)); and ("gypsum" AND (crystal habit OR aggregation) AND (particle sizing OR dispersion)). Sources were selected for direct relevance to mineral occurrence, measurement reliability, mineral liberation, separation, or process-design translation. This is a structured critical narrative review—not a systematic review or meta-analysis—and no exhaustive database coverage, recorded citation-chaining protocol, complete screening ledger, or PRISMA flow is claimed. In the narrative, results from direct PG–REE investigations are distinguished from direct PG purification, gypsum analogs, and methodological evidence. The reference corpus comprises 87 entries after adding three verified contemporary reviews.

Table 1. Classification of evidence relevant to PG–REE separability

Evidence class	Direct inference supported	Key limitation
Direct PG–REE	Phase occurrence, assays, and measured recovery	Sample-specific; often incomplete liberation data
Direct PG purification	Impurity removal and gypsum separation	May not measure REE deportment
Synthetic gypsum/analog	Crystal habit or method behavior	No automatic transfer to PG
Conceptual/methodological	Study design, uncertainty, and scale-up	Not experimental proof

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Note. Conceptual evidence and measurement framework; no numerical measurements are implied.

Table 1 separates evidence that can support a PG-specific REE separation decision from studies that establish only general characterization or gypsum-purification mechanisms. The latter provide hypotheses to test, not quantitative beneficiation performance.

2. Particle Formation and Textural Characteristics of Phosphogypsum

Wet-process conditions—including phosphoric acid concentration, sulfate supersaturation, temperature, mixing, residence time, and soluble impurities—affect nucleation, subsequent gypsum growth, and the capture or adsorption of minor elements. Therefore, the resulting PG is not one mineralogically uniform solid but a process-dependent assemblage of crystals, intergrowths, adhered fines, and entrained process liquor. (Lei et al., 2024; Li et al., 2024; Li et al., 2026)

The distinction between incorporated REE ions, REE-rich discrete particles occluded within gypsum, and REE-bearing phases adhered to external surfaces is decisive. An occluded grain may require breakage to become physically accessible, whereas an adsorbed surface species may be removed chemically without size reduction. A solid-solution-associated element may not form a recoverable discrete mineral at any practical grind size. (Li et al., 2024; Madeja et al., 2023)

The importance of provenance is exemplified by the contrasting mineralogical associations reported for PG from different phosphate-rock origins (Bellefqih et al., 2026). A liberation-based physical route should therefore be evaluated only after distinguishing discrete REE-bearing grains from lattice-hosted or chemically dispersed REEs in the actual feed. The latter cannot be assumed to respond to finer grinding.

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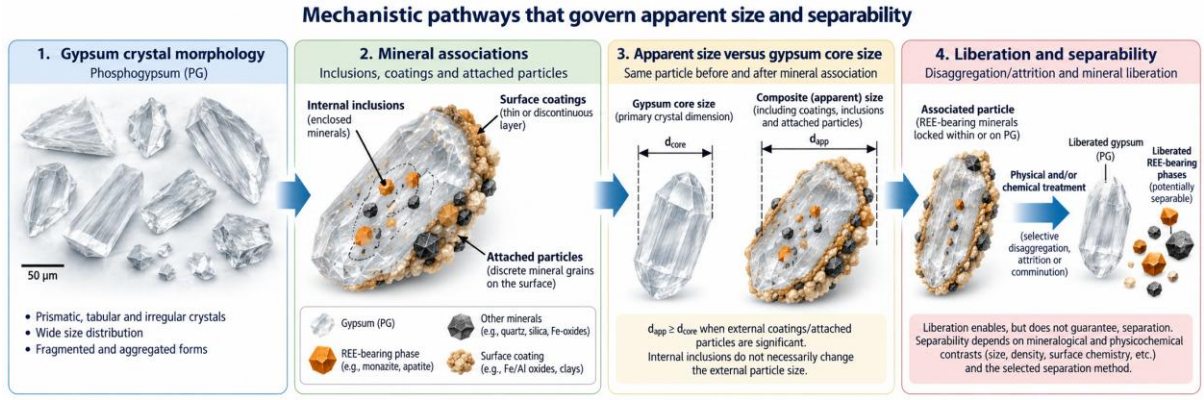

Figure 1. Textural origins of particle-size and liberation constraints.
Note. Original conceptual schematic created for this manuscript; relationships are qualitative.

Comparative literature should therefore be stratified by phosphate ore origin, acid-plant conditions, washing history, and storage/weathering history. Phase attribution based only on bulk XRD peaks or elemental maps is inadequate at low REE concentrations; complementary imaging and microanalysis are needed before selecting a separation mechanism. (Malaie et al., 2021; Peng et al., 2025; Rabizadeh, 2023)

3. Particle Size Distribution and Classification Methods

Particle size is method-dependent. Laser diffraction generally reports an optical equivalent-sphere distribution sensitive to dispersion protocol and refractive index. In contrast, sieve analysis estimates passage through apertures and may respond differently to needles, plates, and fragile clusters. Sedimentation-based measurements reflect hydrodynamic behavior, shape, and effective density rather than a unique physical diameter. (Ben Ali et al., 2025; Ding et al., 2024; Ferhaoui et al., 2022)

Dry measurement may retain aggregates that disperse under wet analysis. Conversely, vigorous ultrasonic dispersion or chemical dispersants can alter fragile gypsum particles and destroy the structure one hopes to characterize. A useful PG characterization program therefore reports the wet/dry protocol, dispersant identity, sonication energy, measurement repeatability, and whether the objective is primary crystal size or operational aggregate size. (Abdel-Aal et al., 2024; Ben Ali et al., 2025; Pereira, 2026d)

For reproducibility, laser diffraction should report the optical model and refractive-index inputs, measurement medium, dispersant dose, dispersion time and intensity, and

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replicate distributions; sieving should report aperture series and operating protocol; sedimentation should state density and fluid assumptions. Where sonication is applied, its nominal specific energy may be expressed as $E_s = P \times t / m_s$ (J kg^{-1} dry solids), with actual delivered power and the uncertainty of the estimate disclosed. Wet- and dry-dispersed size metrics should not be treated as physically interchangeable.

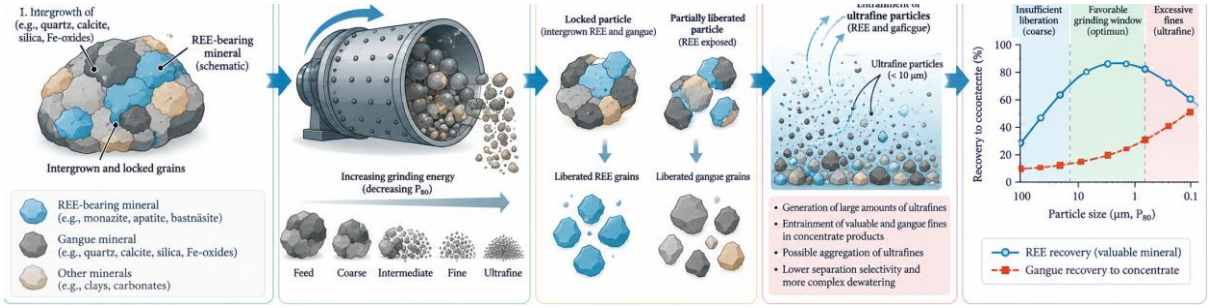

Figure 2. Complementary sampling, sizing, and phase-analysis workflow.
Note. Original conceptual schematic created for this manuscript; relationships are qualitative.

Establish classification efficiency from feed and product mass flow, complete size distributions, and size-specific phase assays. A smaller d_{80} or a shifted laser-diffraction curve cannot substitute for measured partition to underflow and overflow, nor can it establish enrichment of REE-bearing phases without corresponding elemental closure. (Ding et al., 2024; Ferhaoui et al., 2022; Pereira, 2026c)

4. Gypsum Crystal Morphology and Particle Habit

Gypsum crystals may exhibit tabular, prismatic, acicular, or irregular habits depending on growth conditions and impurity adsorption. Such morphologies control projected dimensions, packing, breakage planes, hydraulic settling, and interactions with flotation bubbles. Hence, the same reported median diameter can conceal markedly different separation behavior. (He et al., 2024; Wang et al., 2026; Zhu et al., 2023)

Morphology descriptors should include aspect ratio, circularity, solidity, equivalent area diameter, and, when feasible, thickness inferred from complementary methods. Two-dimensional SEM measurements can characterize habit but not uniquely recover three-dimensional shape or internal inclusion depth. (He et al., 2024; Kakar et al., 2026; Lei et al., 2024)

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When morphology is inferred from image analysis, record the number of particles and size fractions analyzed, field selection, magnification, spatial calibration, image segmentation rules, and particle orientation bias. The equivalent-area diameter and aspect ratio are two-dimensional descriptors; uncertainty from polishing, projection, and nonrandom orientation should be disclosed.

Crystal growth modifiers provide useful mechanistic evidence, but results from laboratory-grown gypsum should not be transferred directly to industrial PG, where dissolved impurity suites and aging histories differ. A defensible model connects observed habit changes to measured changes in liberation and phase-selective partitioning rather than presuming that morphological regulation is intrinsically beneficial. (Li et al., 2024; Madeja et al., 2023; Malaie et al., 2021)

5. Particle Aggregation, Agglomeration, and Surface Coatings

Aggregation can produce an apparent coarse fraction enriched in fine contaminant particles. Electrostatic attraction, bridging by soluble salts or colloids, incomplete washing, and precipitation of secondary phases can create coatings that confound SEM imaging, laser sizing, and flotation interpretation. (Abdelouahhab et al., 2024; Cai et al., 2021; Cánovas et al., 2019)

Attrition scrubbing, controlled washing, dispersion, and mild ultrasonic treatment can be compared with comminution as different interventions. Attrition targets surface attachment; grinding targets structural intergrowth; chemical washing targets soluble species. Each intervention must be tied to a specific hypothesized mechanism and then evaluated by phase-resolved deportment. (Ennaciri et al., 2024; Guan et al., 2024; Jia et al., 2025)

Surface attachment, operational agglomeration, salt bridging, precipitated coatings, and true crystallographic inclusion are separate mechanisms. Controlled washing, mild attrition, and breakage should be compared as mechanism-specific treatments, with pre- and post-treatment REE assays of all solids and liquor streams to establish whether apparent cleaning represents selective REE beneficiation.

Operational trade-offs include increased fines formation, loss of valuable phases to slimes, greater filtration burden, and wash-water generation. A successful surface-cleaning step improves separability only if the liberated contaminant fraction can subsequently be rejected

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without disproportionately losing REEs. (Li, J., Li, Y., et al., 2026a; Li, J., Wu, et al., 2026b; Li et al., 2023)

6. Mineral Inclusions and Textural Associations of REE-Bearing Phases

REE may occur in discrete mineral inclusions, phosphate-associated phases, sulfate-bearing phases, or more dispersed structural and surface associations. Different occurrence modes imply different degrees of physical liberation. For example, a small monazite-like inclusion in a gypsum crystal differs fundamentally from REE distributed over a large sulfate host lattice. (Adu et al., 2026; Ait Brahim et al., 2022; Ait Hak et al., 2023)

BSE images and SEM–EDS maps should be combined with quantitative phase analysis and, when warranted, EPMA or micro-XRF to test whether apparent elemental hotspots are discrete grains or mixed interaction volumes. Spatial coincidence between calcium, sulfur, and REEs alone cannot establish either solid-solution substitution or the existence of a unique REE-rich mineral. (Akfas et al., 2023; Akla et al., 2024; Barbosa et al., 2025)

Elemental co-location in an SEM–EDS map indicates spatial association within the interaction volume, not proof of a unique mineral phase or crystallographic substitution. The mineralogical report should disclose spatial resolution, detection limits, phase-library assumptions, the unassigned fraction, and any cross-validation by EPMA, micro-XRF or phase-sensitive techniques.

The key output is a deportment inventory that assigns total REE mass to mineral and textural association classes, with an explicit unassigned fraction. Uncertainty increases when phases fall below beam-resolution limits, when reference spectra overlap, or when process liquor residues distort the observed composition. (Bellefqih et al., 2026; Brückner et al., 2020; Chanouri et al., 2024)

7. Liberation Analysis and Mineral Association Quantification

Automated mineralogy systems such as MLA and QEMSCAN can quantify exposed phase area, particle association, and liberation classes when classification libraries and imaging resolution are appropriate. However, their apparent precision should not be conflated with accuracy: poorly resolved REE-bearing grains and low-concentration substitution can be misclassified as host gypsum. (Ferreira et al., 2024; Kirillov et al., 2026; Lütke et al., 2020)

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Liberation must be defined explicitly—for example, by exposed REE-phase area fraction or by the fraction of particles above a stated liberation threshold. Size-bin distributions should be mass-weighted, and authors should acknowledge the stereological limitations of polished-section imaging. Surface exposure and three-dimensional accessibility may differ significantly. (Pereira, 2026c; Rerani et al., 2024; Rychkov et al., 2018)

For image-derived liberation, one explicit area-based definition is L_A = A(target phase exposed at particle boundary) / A(total target phase in the observed section). A complementary mass-weighted metric is L_x = m(target phase in particles above x% liberation) / m(total target phase). The threshold x, analysis basis (area versus mass), particle count, grain-resolution cutoff and stereological limitations must accompany any percentage. Section exposure must not be equated with three-dimensional accessibility.

An internally consistent workflow measures bulk mineralogy, size-by-size chemical assays, image-derived association, and product mass yields on matched aliquots. A normalized, phase-specific recovery metric allows comparisons across screening, selective breakage, and chemical pretreatment, but only when the target phase is demonstrably discrete. (Barbosa et al., 2025; Ferreira et al., 2024; Uliana et al., 2025)

For size class i, the fractional REE inventory is expressed as:

$$D_i = (m_i \times C_i) / \Sigma_j(m_j \times C_j) \quad (1)$$

Here D_i is the dimensionless fraction of the measured REE inventory assigned to size class i, m_i is its dry mass (kg), and C_i is its REE concentration on the same dry basis (mg kg^{-1}). The sum is evaluated across mutually exclusive, completely recovered fractions. The equation is an accounting identity rather than an empirical liberation model.

A separate feed-to-fractions closure statistic should be reported for each element k: C_k,closure = 100 × $[\Sigma_i(m_i \times C_{i,k})]$ / (m_F × C_$F_{,k}$) (%). The numerator includes all recovered solid fractions and, where relevant, dissolved or lost inventories on a consistent basis. Closure should be assessed for total REEs, individual high-value REEs when quantifiable, and major impurities; material departures from 100% require investigation rather than an arbitrary universal acceptance threshold. Propagate sampling, splitting and analytical uncertainties,

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including their correlations where material, and report replicate assays and confidence intervals when justified.

Table 2. Minimum measurement package for size-resolved mineral liberation

Measurement	Required outputs	Failure if omitted
Size distribution	Dry mass by interval; wet/dry dispersion response	False fraction attribution
REE and major-element chemistry	La–Lu, Y, Sc assays and closure	Grade–recovery ambiguity
Quantitative mineralogy	Phase abundance, grain association	No mineral-specific mechanism
Automated imaging	Liberation class by size; resolution limits	Inaccessible vs liberated conflated
Process split tests	Partition, recovery, and reagent use	No equipment design basis

Note. Conceptual evidence and measurement framework; no numerical measurements are implied.

These measurements must be made on representative, matched aliquots. Agreement among particle sizing, chemistry, and mineralogy provides a stronger basis for choosing a separation operation than any one technique considered independently.

8. Comminution Response and Selective Breakage

Comminution may expose occluded REE-bearing inclusions, but gypsum fragmentation is not inherently selective relative to accessory phases. More energy can reduce host-particle size faster than it increases separation contrast, producing ultrafine slimes, mixed fragments, and deteriorating solid–liquid handling. (Chen et al., 2025; Jia et al., 2025; Zhang et al., 2026)

Controlled tests should include multiple energy inputs, particle-size distributions, size-specific REE grades, image-based liberation, and paired phase recovery measurements. The objective is to identify the marginal gain in recoverable liberation per unit of additional grinding energy rather than maximizing fineness. (Chen et al., 2025; Jia et al., 2025; Zhang et al., 2026)

Incremental liberation and metallurgical response should be distinguished. Conceptual comparison metrics are $G_L = \Delta L / \Delta E_{grind}$ and $G_R = \Delta R_{REE} / \Delta E_{grind}$, where energy is specific grinding energy. The latter is closer to process value because additional liberated

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surface may not translate into selectively recovered REEs. These ratios require paired tests and are not estimates of optimum grinding energy in the absence of experimental data.

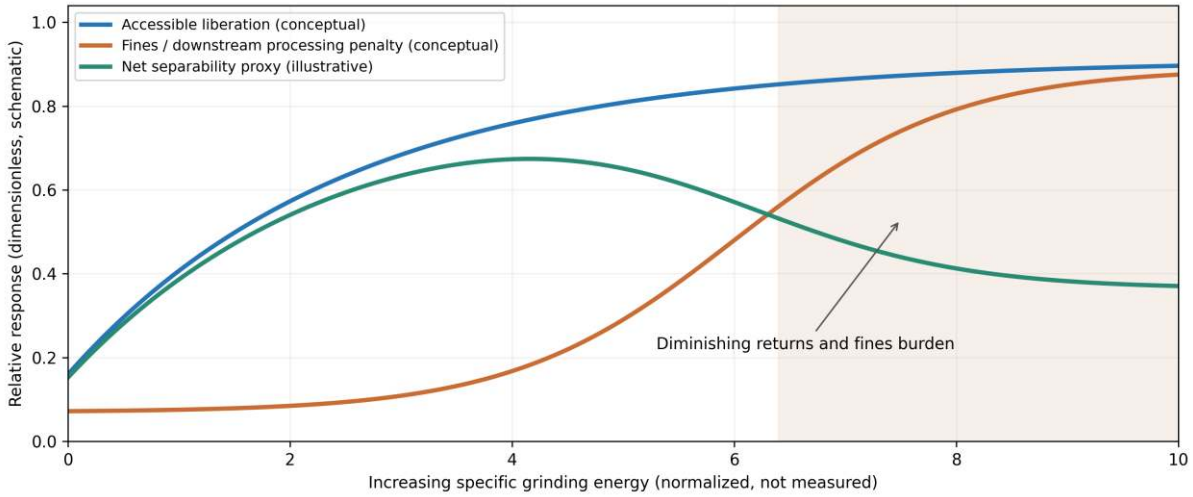

Figure 3. Conceptual trade-off between liberation and excessive fines.
Note. Original conceptual schematic created for this manuscript; relationships are qualitative.

Figure 3 distinguishes three outcomes: liberation increases, breakage produces little additional liberation because REE is structurally dispersed, or excessive fines diminish downstream selectivity. Studies on unrelated ores illustrate possible mechanisms but cannot define an optimum grind for PG without feed-specific testing. (Chen et al., 2025; Jia et al., 2025; Zhang et al., 2026)

The curves in Figure 3 are illustrative and dimensionless, not fitted to a PG experiment. They express the competing hypotheses that accessible liberation may initially increase with grinding intensity, fines and handling penalties may become dominant, and net separability may therefore peak before maximum fineness. The position or existence of such an optimum is source-specific and must be determined experimentally.

9. Size-Dependent REE Enrichment and Mineralogical Distribution

An REE-enriched size fraction is meaningful only with both concentration and mass distribution reported. A high grade in a small fraction can contribute little to overall REE recovery, whereas a modestly enriched, high-yield fraction can be a more attractive physical-processing target. (Diwa et al., 2023; Gasser et al., 2022; Gijon et al., 2026)

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For each size class i, the share of the feed REE inventory in that class equals its dry mass fraction multiplied by its REE grade, divided by the mass-weighted feed grade. This is inventory deportment, not recoverable REE yield: actual recovery additionally requires measured partitioning and extraction efficiency. Reporting concentration ratios without fraction mass yield may therefore misrepresent potential process value. Handle loss-on-ignition and moisture corrections consistently. (Guan et al., 2022a; Habibi et al., 2026; Hammas-Nasri et al., 2016)

Observed fractionation can arise from primary crystal dimensions, adhered fines, mineral inclusion frequency, or grinding-induced redistribution. Mechanistic discrimination demands microscopy and mineral association data on the same fractions. A positive correlation of grade with fineness does not establish that additional comminution is beneficial. (Jin et al., 2025; Khalil et al., 2025; Kulczycka et al., 2016)

10. Implications for Screening, Classification, and Desliming

Screening and hydraulic classification should be treated as candidate separation operations with measurable partition curves rather than as generic preprocessing. Density, particle habit, agglomeration, and fluid rheology may decouple size from sedimentation behavior, particularly for fine or platy gypsum. (Chahardahmasoumi et al., 2026; Chen et al., 2025; Du et al., 2025)

A practical classification trial should collect full feed, coarse product, fine product, and wash streams; measure flow and solids concentrations; and assay individual REEs and major impurities. Partition correction for bypass and misplaced material is essential before attributing enrichment to selective classification. (Fang et al., 2022; Jia et al., 2025; Li et al., 2024)

For each partition test, establish the dry-solid feed and product masses, water flows, particle-size distributions, concentrations of individual REEs, total REE inventory and impurity assays. Correct classification partition curves for hydraulic bypass when appropriate. Report $R_{REE} = 100 \times$ (REE mass in retained target stream)/(REE mass in the feed), and distinguish REE loss to discarded slimes from improvement in gypsum purity.

Desliming may increase the stability of a downstream flotation circuit yet discard REE-rich fines. Consequently, the criterion must be valuable-element recovery and net rejectable

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mass, not merely cleaner coarse gypsum or reduced slurry viscosity. (Li et al., 2025; Qi et al., 2023; Shi et al., 2025)

Table 3. Screening and classification trade-offs for PG

Candidate operation	Potential benefit	Critical verification
Wet screening	Reject coarser impurity aggregates	REE distribution in each product
Hydrocyclone classification	Separate fine-rich and coarse-rich streams	Density, shape, and bypass correction
Desliming	Improve some separation responses	REE losses to slimes
Attrition plus classification	Detach surface-bound particles	Breakage, water use, and phase recovery

Note. Conceptual evidence and measurement framework; no numerical measurements are implied.

Table 3 distinctions should be resolved experimentally through product-mass accounting and REE assays. Nominal cut size alone does not reveal whether a classification step increases REE recovery or merely discards material.

11. Liberation Constraints on Physical Separation Technologies

Flotation studies establish that gypsum and silicate impurities can show distinct surface-chemical behavior under selected reagent conditions. Nonetheless, removing quartz from PG should not be interpreted as recovering REE minerals unless the REE distribution in both products is measured. (Chanouri et al., 2024; Kurkinen et al., 2021; Lu et al., 2023)

Gravity concentration requires an effective contrast in settling behavior and adequate liberation. Ultrafine entrainment and complex particle shapes reduce the predictive value of nominal mineral density. Magnetic and electrostatic separation may be technically plausible for specific discrete accessory phases, but they require verified mineral occurrence and preconditioning. (Maina et al., 2024; Masmoudi-Soussi et al., 2020; Mukaba et al., 2021)

For flotation, recovery of silica or improvement in gypsum purity is not equivalent to recovery of REEs: assay both concentrate and tailings and reconcile their dry masses and element inventories. Gravity, magnetic and electrostatic separation should be considered only where the target association is discrete, sufficiently liberated and exhibits a verified separable property contrast. Direct whole-feed leaching remains an appropriate comparator for any proposed hybrid route (Nkabinde et al., 2026).

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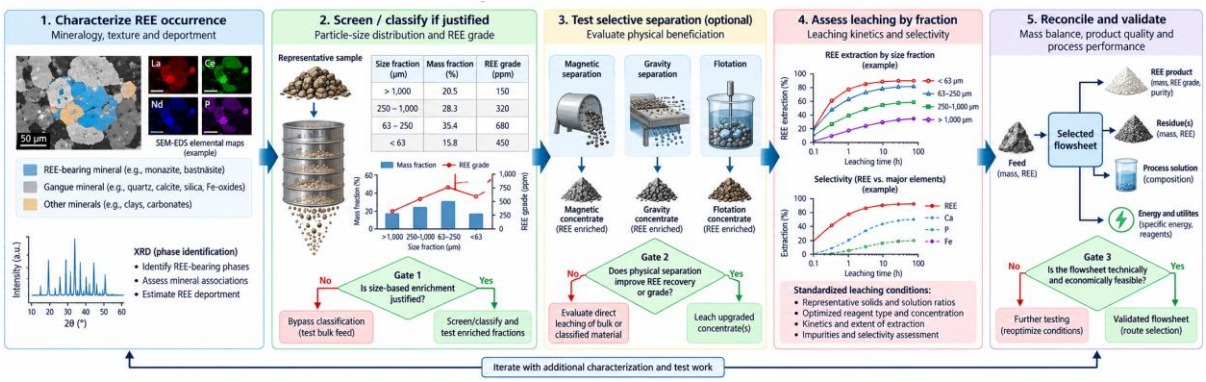

Figure 4. Evidence-based selection of beneficiation and downstream routes.
Note. Original conceptual schematic created for this manuscript; relationships are qualitative.

Hybrid schemes can combine gentle dispersion, classification, selective flotation, and leaching of separated fractions. Proper performance criteria include REE recovery, concentration ratio, gypsum mass rejection, reagent consumption, water demand, and downstream residue quality. Figure 4 presents a decision framework that avoids selecting technology before establishing the target phase. (Pereira, 2026a; Pereira, 2026e; Qing et al., 2025)

12. Experimental Limitations and Scale-Dependent Characterization

PG stacks exhibit spatial heterogeneity associated with source ore, plant operation, storage age, weathering, and water movement. A single grab sample cannot support robust flowsheet selection. A hierarchical sampling plan should represent both bulk stockpile variability and the smaller-scale variability introduced during splitting, wet sizing, and mineralogical mounting. (Ennaciri et al., 2020; Maina et al., 2026; Pereira, 2026c)

The uncertainty budget should distinguish primary sampling heterogeneity, sample preparation and splitting, and analytical measurement. This distinction is essential where low REE grades or small apparent enrichment factors make a calculated improvement comparable to measurement error. Independent replicate separations, certified reference materials or suitable matrix-matched quality controls, blanks and documented reporting limits should be used as applicable.

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Analytical limitations include particle aggregation, contamination during grinding, detection limits for individual REEs, nonrepresentative polished sections, mineralogical model sensitivity, and unclosed mass balances. Replicate assays, blanks, standards, and independent methods should be selected relative to the magnitude of the proposed enrichment effect. (Akfas et al., 2023; Ennaciri et al., 2020; Ricardo et al., 2024)

Laboratory improvements in purity or leaching may not translate to plant design because of solids residence-time distributions, scaling, water recycle, reagent carryover, and filtration. Scale-up should therefore focus on preserving the governing separation mechanism and using integrated pilot mass balances rather than nominal equipment similarity alone. (Guan et al., 2022a; Habibi et al., 2026; Kirillov et al., 2026)

Table 4. Evidence gates before moving to process design

Gate	Minimum acceptance evidence	Decision if not demonstrated
Occurrence	REE host phases identified	Prioritize phase identification
Liberation	Quantified, resolution-qualified size dependence	Do not assume finer grinding
Separation	Closed size-by-size REE mass balance	Do not claim preconcentration
Translation	Replicates, water and solids balances	Limit process readiness claims

Note. Conceptual evidence and measurement framework; no numerical measurements are implied.

Passing the gates in Table 4 reduces the risk of selecting equipment based on a favorable single test that does not persist when slurry characteristics, recycle loads, and feed variability are considered.

The four gates are noncompensatory: success in one gate does not substitute for missing evidence at another. In particular, a high apparent extraction rate cannot establish occurrence, liberation or physical preconcentration without quantitative phase and stream accounting. Pilot testing should report operating duration, feed variability, slurry rheology, recycle water, reagent carryover and residence-time behavior before industrial readiness is asserted.

13. Conclusions

Particle size alone is an insufficient design variable for recovering rare earth elements from phosphogypsum. The decisive quantity is the recoverable distribution of REE-bearing

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phases among size classes and their mineralogical associations, constrained by the host crystal morphology and the mechanism of particle aggregation.

Physical upgrading is warranted when size-by-size mass balances and phase-resolved microscopy show a discrete, separable REE-bearing fraction. Grinding is justified only when additional liberation improves downstream separation without unacceptable losses to fine particles. Where REEs are structurally dispersed in gypsum, chemical extraction or hybrid routes are more credible starting points.

The proposed characterization-to-design framework calls for representative sampling, complementary particle-sizing measurements, quantitative mineralogy, controlled breakage and scrubbing tests, and closed partition balances. The principal research gap is direct, replicated quantification of REE-phase liberation and recovery potential under operating conditions representative of industrial PG.

Declarations

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Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

Author Contributions

The author performed conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation.

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