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Recovery of Rare Earth Elements and Co-Products from Eudialyte-Group Minerals: Mineralogical Controls, Silica Management, and Integrated Hydrometallurgy (2010–2025): A Critical Review

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Abstract

Eudialyte-group minerals (EGMs) are unconventional zirconosilicate resources that host rare earth elements (REEs), yttrium, zirconium, hafnium, niobium, manganese, and other high-field-strength elements within a chemically reactive but process-complex matrix. Their relevance as alternative REE feedstocks depends not on bulk grade alone, but on deposit-specific heavy-REE distributions, comparatively low uranium and thorium contents in many occurrences, and the potential to recover multiple co-products. This critical review evaluates processing literature published from 2010 through 2025 and examines the causal links among crystal chemistry, feed mineralogy, beneficiation, acid decomposition, silica behavior, solid-liquid separation, downstream purification, co-product recovery, scale-up, and environmental performance. Across the evidence base, the principal technical challenge is not simply achieving high elemental dissolution; it is controlling silicon release and polymerization while maintaining filterability, limiting acid demand, minimizing adsorption and coprecipitation losses, and generating liquors suitable for selective separation. Direct acid leaching can achieve substantial extraction under relatively mild conditions, whereas dry digestion, staged contact, and other low-water strategies provide stronger control when silica gelation governs operability. Nitric-acid and energy-assisted routes expand the design space, while bioleaching and organic-acid routes remain less mature for high-throughput primary processing. Downstream design increasingly shifts the flowsheet objective from a single REE product toward coordinated recovery of REEs, Zr–Hf, and Nb, with impurity and residue management integrated from the outset. The central research need is therefore systems-level optimization of mineral liberation, water activity, reaction pathway, filtration, recycle, impurity bleed, and co-product specifications. A route that maximizes batch extraction may still

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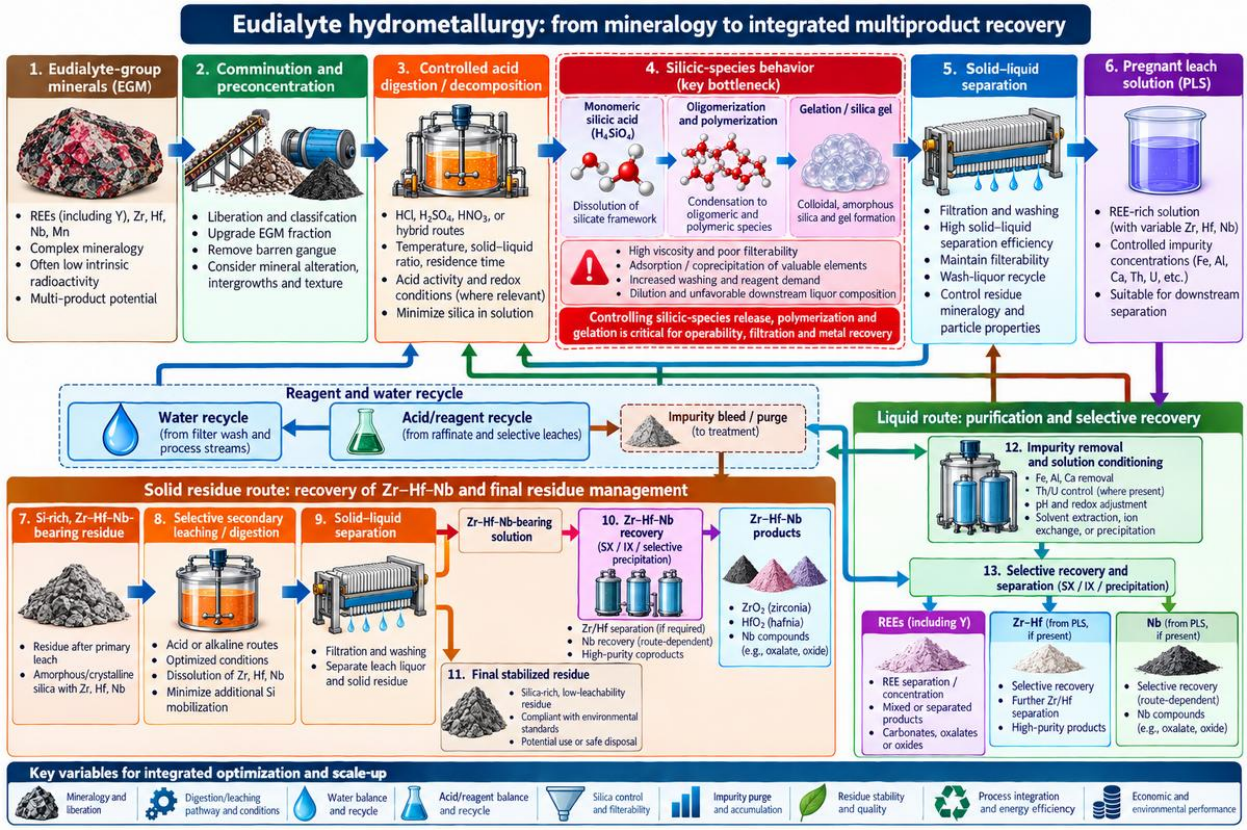
underperform at plant scale if it produces unfilterable silica, dilute liquors, excessive recycle burden, or unrecoverable metal losses.

Keywords: Eudialyte; rare earth elements; hydrometallurgy; silica gel; zirconium; process integration

Highlights

- Silica control, rather than acid strength alone, governs process operability.
- Dry digestion and staged leaching decouple metal dissolution from silica gelation.
- Co-recovery of REEs, Zr–Hf, and Nb is central to integrated eudialyte value.
- Scale-up requires coupled water, acid, filtration, recycle, and residue balances.

Graphical abstract



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1. Introduction

Rare earth elements (REEs) are often treated as a single commodity group; however, process design depends on mineral host, elemental deportment, gangue reactivity, impurity behavior, and the distribution of light and heavy REEs. Eudialyte-group minerals (EGMs) are important in this context because they are complex Na-Ca-Mn-Fe zirconosilicates that can host Zr, Hf, Nb, Y, and lanthanides in several crystallographic sites. Their economic significance is therefore not adequately represented by total REE grade alone. Crystal chemistry, liberation, alteration, and co-product potential jointly determine whether a given EGM-bearing ore can support a practical hydrometallurgical flowsheet (Borst et al., 2016, 2020; Kogarko & Nielsen, 2020, 2021; Sjöqvist et al., 2013, 2020).

The modern processing literature has converged on a central paradox. Eudialyte is sufficiently acid-reactive to permit substantial dissolution under comparatively mild conditions, yet the same reactivity releases silicon species that can polymerize into gelatinous phases. The resulting gel can increase slurry viscosity, compromise filtration, entrain mother liquor, adsorb valuable metals, and convert an apparently favorable extraction result into an operationally poor flowsheet outcome. Consequently, process performance should be judged using a coupled set of criteria: metal recovery, dissolved-silica concentration, filterability, acid consumption, solution purity, residue quality, water demand, and downstream separability (Balinski et al., 2019a, 2019b, 2020; Davris et al., 2017; Silin et al., 2024; Voßenkaul et al., 2017).

This review treats eudialyte processing as an integrated mineral-to-product problem. Table 1 summarizes the mineralogical variables that control process response, and Table 2 condenses representative feed and deposit implications. Figure 1 presents the critical path from ore mineralogy to REE and co-product recovery, whereas Figure 2 explains why silicon chemistry is the dominant operability constraint. Table 3 and Figure 3 compare the principal decomposition-

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route families. Table 4 integrates downstream separation choices, and Figure 4 synthesizes the complete process logic, including internal recycle and residue valorization. Finally, Table 5 translates the reviewed evidence into plant-relevant scale-up criteria and research priorities.

The objective is not to identify a universally superior reagent. Instead, the review addresses four process-level questions. First, which mineralogical features control liberation and dissolution? Second, which reaction pathways maximize recoverable metals without entering the silica-gel regime? Third, how should REE recovery be coordinated with Zr–Hf–Nb recovery and impurity removal? Fourth, which performance indicators are missing from current laboratory studies and are required for credible pilot-scale and techno-economic assessment? This framing distinguishes chemical extraction from process viability, which is essential for a critical review of a feed whose principal challenge is coupled reaction and separation behavior.

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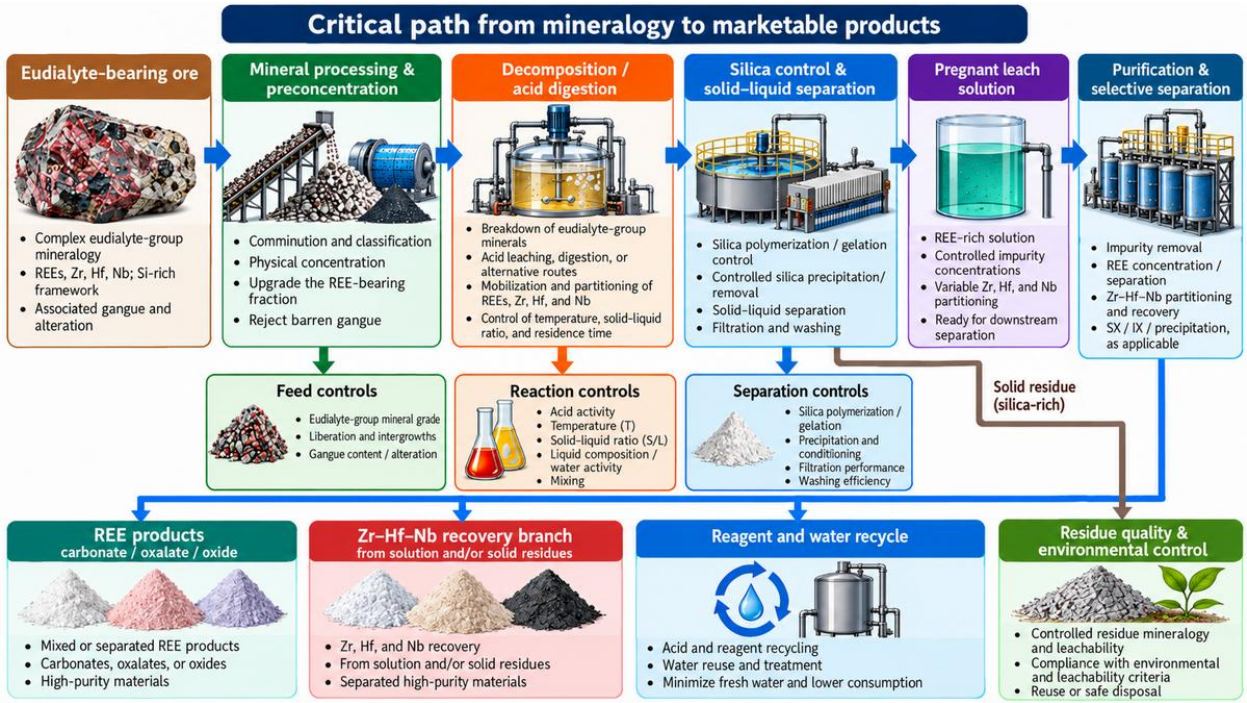

Figure 1
Critical path linking eudialyte mineralogy, decomposition, silica control, and product recovery
Note. Original synthesis adapted from the integrated processing logic reported by Balinski et al. (2019a, 2020), Balomenos et al. (2017), Ma et al. (2019a), Nechaev and Polyakov (2025), and Voßenkaul et al. (2017).

2. Review scope, evidence base, and critical appraisal framework

The evidence base comprises peer-reviewed studies and technically traceable conference literature published mainly from 2010 through 2025, with older foundational work retained only where it directly informs contemporary flowsheets. The review is structured as a critical narrative synthesis rather than a statistical meta-analysis. The corpus spans crystal chemistry and resource characterization, beneficiation, acid and hybrid decomposition, energy-assisted leaching, sorption conversion, precipitation, solvent extraction, ion exchange, co-product recovery, pilot-scale

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testing, and life-cycle assessment. The scope is intentionally broader than a leaching review because the dominant process failures often occur at the interfaces between unit operations rather than within a single reaction step.

Mineralogical and crystallographic studies were used to establish how site occupancy, compositional variability, alteration, and deposit-specific textures affect process response (Borst et al., 2016, 2020; Goodenough et al., 2016; Kogarko, 2023; Kogarko & Nielsen, 2020, 2021; Mikhailova et al., 2020, 2022a, 2022b; Panikorovskii et al., 2021; Pfaff et al., 2010; Rastsvetaeva & Chukanov, 2012, 2020; Schilling et al., 2011; Sjöqvist et al., 2013, 2020; van de Ven et al., 2019). Processing studies were appraised according to feed characterization, reagent concentration, temperature, solid-to-liquid ratio, contact sequence, water activity, extraction, silica behavior, solid-liquid separation, solution purity, downstream recovery, recycle, and demonstration scale (Balinski et al., 2019a, 2019b, 2020; Bogatyreva et al., 2018a, 2018b, 2018c; Chanturia et al., 2017, 2019, 2020, 2021; Chanturiya, 2022; Chanturiya et al., 2021, 2022, 2023, 2024; Davris et al., 2017; Lokshin & Tareeva, 2020; Lokshin et al., 2020, 2022, 2023; Ma et al., 2018a, 2018b, 2019a, 2019b, 2020; Matveev et al., 2018; Nechaev & Polyakov, 2025; Voßenkaul et al., 2017). Because feed compositions, reactor configurations, and reporting bases vary substantially, we did not pool extraction percentages across dissimilar studies.

This review deliberately distinguishes between extraction metrics and flowsheet metrics. We did not treat high extraction as evidence of process superiority unless the study also demonstrated manageable silicon behavior, acceptable reagent demand, separable solids, and a credible purification route. Likewise, researchers did not assume environmentally attractive routes were scalable when kinetics, pulp density, product concentration, or reagent recycling remained unresolved. Bioleaching and lower-severity alternatives were therefore assessed on process

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intensity and throughput as well as reagent identity (Hedrich et al., 2023; Talan & Huang, 2022; Zapp et al., 2022).

3. Mineralogical and crystal-chemical controls on process response

EGMs form an unusually flexible zirconosilicate structural family. Their framework and extra-framework sites accommodate Na, Ca, Fe, Mn, Zr, Ti, Nb, Sr, Y, REEs, Cl, OH, H_2O, and other species, and this compositional flexibility produces substantial variability among deposits and even within a single intrusive complex. Structural work indicates that REEs preferentially occupy Ca-dominant sites and that local Ca-Mn ordering can influence heavy-REE accommodation. This matters hydrometallurgically because the first stages of acid attack remove alkalis and other labile cations before the more polymerized Zr-Si framework is completely destroyed (Borst et al., 2020; Kogarko & Nielsen, 2021; Mikhailova et al., 2022a; Pereira, 2025).

The term “eudialyte concentrate” therefore conceals important feed variability. Changes in Fe/Mn, Na, Ca, Zr, Nb, Sr, Cl, REE + Y, and alteration products can affect acid neutralization, redox behavior, salt formation, and the quantity and character of residual silica. Hydrothermal alteration may partially dissolve primary EGM and produce secondary Zr-silicate or REE-bearing phases, thereby changing both liberation and leaching response. Deposit-specific mineralogical characterization must therefore precede reagent optimization rather than be treated as a descriptive appendix (Borst et al., 2016; Kogarko & Nielsen, 2020, 2021; Mikhailova et al., 2020, 2022a; van de Ven et al., 2019).

Table 1 summarizes the mineralogical attributes most relevant to processing. The synthesis emphasizes a recurring conclusion in the literature: mineralogical complexity changes the recovery route, not merely the theoretical quantity of recoverable metal.

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Table 1
Critical mineralogical attributes of eudialyte-group minerals relevant to hydrometallurgical processing

Mineralogical attribute	Processing consequence	Required characterization	Design response
REE and Y distribution among Ca-rich sites	Influences dissolution sequence and value distribution	EPMA/LA-ICP-MS; mineral-specific REE patterns	Base route selection on deportment, not total REE (TREE) grade
Zr-Si framework stability	Controls residual phases and secondary Zr recovery	XRD, Raman, and SEM-EDS before and after leaching	Plan a dedicated Zr-Hf-Nb branch when retention is intentional
Na-Ca-Mn-Fe variability	Changes acid demand, ionic strength, and precipitate chemistry	Modal mineralogy plus whole-rock chemistry	Use mineral-based acid balance and impurity forecast
Hydrothermal alteration and secondary silicates	Can change liberation and leachability	Automated mineralogy; texture mapping	Blend or treat altered domains separately when needed
Gangue and accessory minerals	Drive acid consumption and impurity load	Quantitative mineralogy and neutralization tests	Beneficiate for downstream chemistry, not grade alone

Note. Critical synthesis based on Borst et al. (2020), Kogarko and Nielsen (2021), and Mikhailova et al. (2022a). The table emphasizes process consequences rather than taxonomic distinctions.

4. Beneficiation, preconcentration, and feed preparation

Because EGM ores can have modest bulk REE grades, hydrometallurgical economics depend strongly on rejecting barren or acid-consuming gangue before leaching. Work on Norra Kärr has shown that magnetic separation is applicable to EGM-bearing ore, and later studies examined the recovery of catapleiite and eudialyte from non-magnetic fractions. Together, these studies support a broader process principle: design beneficiation around downstream acid consumption and residue volume, not mineral recovery alone (Silin et al., 2022; Stark et al., 2017; Pereira, 2026a).

Liberation is also a chemical variable. Excessive fine grinding can improve mineral exposure, but it can also increase solid-liquid separation difficulty, entrainment, and reagent consumption, whereas insufficient liberation transfers gangue and locked particles into the digestion stage. The preferred feed is therefore not simply the highest-grade concentrate; it is the concentrate that

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combines adequate EGM exposure, low carbonate or reactive-gangue burden, a controlled particle-size distribution, and acceptable filtration behavior after decomposition. The EURARE work is important in this respect because it treated mineral processing and hydrometallurgy as parts of the same value chain rather than as independent optimization problems (Balomenos et al., 2017; Stark et al., 2017; Voßenkaul et al., 2017).

Table 2 summarizes representative feed contexts and their implications for flowsheet selection. These deposits are not interchangeable; process transfer should therefore be based on mineralogical similarity rather than geographic analogy.

Table 2
Representative eudialyte feed contexts and implications for flowsheet selection

Feed context	Key literature signal	Primary opportunity	Primary process risk
Norra Kärr-type EGM ore	Magnetic separation and direct beneficiation investigated	Preconcentration before hydrometallurgy	Variable liberation and gangue carryover
Ilímaussaq (Greenland) EGM-bearing materials	Zirconosilicate and EGM variability documented	HREE, Y, and high-field-strength-element co-product potential	Mineralogical heterogeneity and accessory phases
Lovozero EGM concentrates	Extensive acid, energy-assisted, and sorption studies	Integrated Zr and REE recovery	Complex liquor chemistry and silica losses
Altered EGM-bearing ore	Hydrothermal modification can redistribute critical metals	Selective treatment of altered domains	Mismatch between fresh-mineral chemistry and actual feed

Note. Critical synthesis based on Balomenos et al. (2017), Kogarko and Nielsen (2021), Mikhailova et al. (2022a), Silin et al. (2022), and Stark et al. (2017).

5. The silica problem: mechanism, losses, and solid-liquid separation

Silica gel formation is the defining separation problem in eudialyte hydrometallurgy. Acid attack on the zirconosilicate framework generates soluble or colloidal silicic species. When concentration, pH, ionic strength, temperature, and residence time favor condensation, these species polymerize into a three-dimensional hydrated network. The operational consequence is not

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merely slow filtration. Gel can immobilize liquid, increase apparent pulp volume, carry dissolved metals into the cake, and provide surfaces for the adsorption or incorporation of REEs and other valuable components (Balinski et al., 2019a; Chanturia et al., 2021; Davris et al., 2017).

Balinski et al. (2019a) demonstrated the trade-off directly in sulfuric acid systems: direct leaching under relatively mild conditions can provide high average recovery of valuable components, but dissolved silica may remain in solution and subsequently gel. Fast leaching and dehydration-based variants seek to force silicon into a separable solid before prolonged aqueous residence. Davris et al. (2017) similarly showed that staged or dry-digestion concepts can maintain high REE recovery while suppressing silicon transfer to the pregnant leach solution (PLS). More recent reactor work confirms that acid-solid contact geometry and contact mode are part of the chemistry because they determine local water activity, heat transfer, mixing, and the rate at which a passivating or filterable silica-rich phase develops (Silin et al., 2024).

Figure 2 illustrates the principal competing strategies. The key design variable is not silica removal after gelation; it is prevention of entry into the gelation window. This reframes filtration as an upstream reaction-design objective rather than a downstream corrective step.

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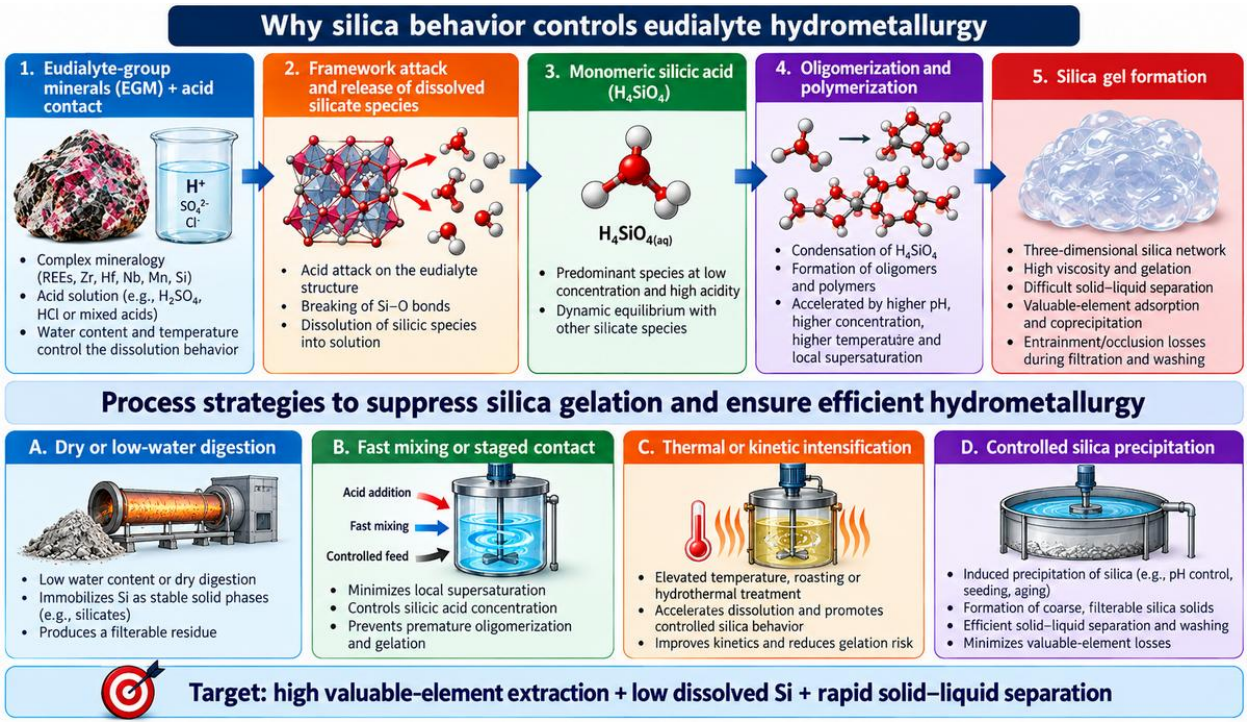

Figure 2
Silicon release, polymerization, and process strategies for avoiding the silica-gel window
Note. Original synthesis adapted from Balinski et al. (2019a), Chanturia et al. (2021), Davris et al. (2017), Silin et al. (2024), and Voßenkaul et al. (2017).

6. Acid decomposition and hybrid leaching routes

Acid systems dominate the modern processing literature because eudialyte is comparatively susceptible to mineral-acid attack. However, hydrochloric, sulfuric, and nitric-acid routes generate different salt matrices, impurity distributions, and downstream constraints. Route selection should therefore be based on the complete flowsheet, including reagent regeneration and product chemistry, rather than on extraction alone (Cheremisina et al., 2020; Nechaev & Polyakov, 2025).

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6.1. Hydrochloric-acid digestion. Low-temperature HCl dry digestion followed by water leaching is among the most developed strategies for suppressing silica gelation. In the EURARE-derived flowsheet, concentrated HCl is contacted with the concentrate under low-water conditions, and the digested material is subsequently water-leached. Ma et al. (2019a) reported high REE leaching and demonstrated impurity precipitation and pilot-scale production of a mixed REE carbonate intermediate. The strength of this route lies not in HCl alone, but in the sequencing of concentrated-acid digestion, controlled water addition, and purification. Its principal liabilities are chloride management, materials of construction, acid recovery, and controlling Zr, Fe, and Al transfer to solution (Ma et al., 2019a; Voßenkaul et al., 2017).

6.2. Sulfuric-acid routes. Sulfuric acid offers lower volatility and potentially favorable reagent cost, but sulfate chemistry creates its own selectivity and precipitation effects. Direct, fast, and dehydration-assisted sulfuric-acid routes have been compared systematically, showing that metal losses can arise from adsorption on silica, double-sulfate formation, and incorporation into secondary phases. Sulfation followed by thermal decomposition of non-REE sulfates offers another way to modify phase selectivity before water leaching. In situ precipitation during sulfuric-acid processing can also separate REEs from a complex liquor and improve subsequent solution purity (Balinski et al., 2019a, 2019b, 2020; Matveev et al., 2018).

6.3. Nitric-acid and sorption-conversion routes. Nitric acid has been investigated both as a leachant and as a medium compatible with sorption-based recovery. Energy-assisted nitric-acid leaching can produce substantial Zr and REE recoveries, and sorption conversion offers a route for coupling mineral decomposition with selective capture. The approach is potentially attractive where downstream sorbent selectivity offsets higher reagent cost, but resin stability, nitrate

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recycle, water balance, and energy demand require greater pilot-scale definition (Chanturia & Ryazantseva, 2024; Chanturiya et al., 2023; Lokshin & Tareeva, 2020; Lokshin et al., 2023).

6.4. Alkaline-acid hybrids. Alkaline pretreatment has been proposed to modify the mineral before acid attack and to alter the behavior of silica and accessory components. Thermodynamic and experimental studies indicate that alkaline-acid processing can modify phase assemblages and improve overall recovery, but it also introduces additional reagent loops and washing requirements that must be justified by selectivity gains. Such routes may be valuable for specific feed compositions, yet their flowsheet complexity is greater than that of optimized acid digestion (Bogatyreva et al., 2018a, 2018b, 2018c).

Table 3 compares the principal route families on a common process basis. Figure 3 then places them conceptually according to solution cleanliness and overall process intensity, emphasizing that greater chemical selectivity does not automatically translate into a superior flowsheet if it creates a costly recycle or separation burden.

Table 3
Critical comparison of eudialyte decomposition and leaching route families

Route family	Process strength	Dominant limitation	Best-fit role
Direct H_2SO_4 leach	Mild conditions can dissolve multiple valuables	Silica gel; co-dissolution; adsorption and coprecipitation losses	Benchmark route and feeds with strong filtration control
Fast/staged acid leach	Short contact can separate silica-forming and dissolution events	Mixing and mass-transfer sensitivity	High-throughput systems with controlled hydrodynamics
HCl dry digestion followed by water leaching	Strong silica suppression; demonstrated product route	Chloride recycle, corrosion, impurity removal	Integrated mixed-REE carbonate production
H_2SO_4 dry digestion	Low dissolved Si; compatible with secondary Zr-Hf-Nb recovery	Acid distribution and heat/mixing control	Sequential multi-product flowsheets

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Route family	Process strength	Dominant limitation	Best-fit role
HNO_3 energy-assisted leach	High Zr/REE extraction; compatible with sorption	Nitrate recycle and energy demand	Feeds where sorption selectivity offsets reagent burden
Alkaline-acid hybrid	Phase modification before acid dissolution	More reagent and wash loops	Specific feeds where silica/gangue chemistry justifies pretreatment
Bioleaching/organic-acid route	Lower-severity chemistry	Slow kinetics and dilute products	Low-grade or secondary feeds; niche applications

Note. Route rankings are deliberately avoided because suitability depends on feed mineralogy, silica behavior, recycle, and downstream product requirements. Critical synthesis based on Balinski et al. (2019a, 2019b, 2020), Bogatyreva et al. (2018a, 2018b, 2018c), Chanturiya et al. (2023), Davris et al. (2017), Hedrich et al. (2023), and Ma et al. (2019a).

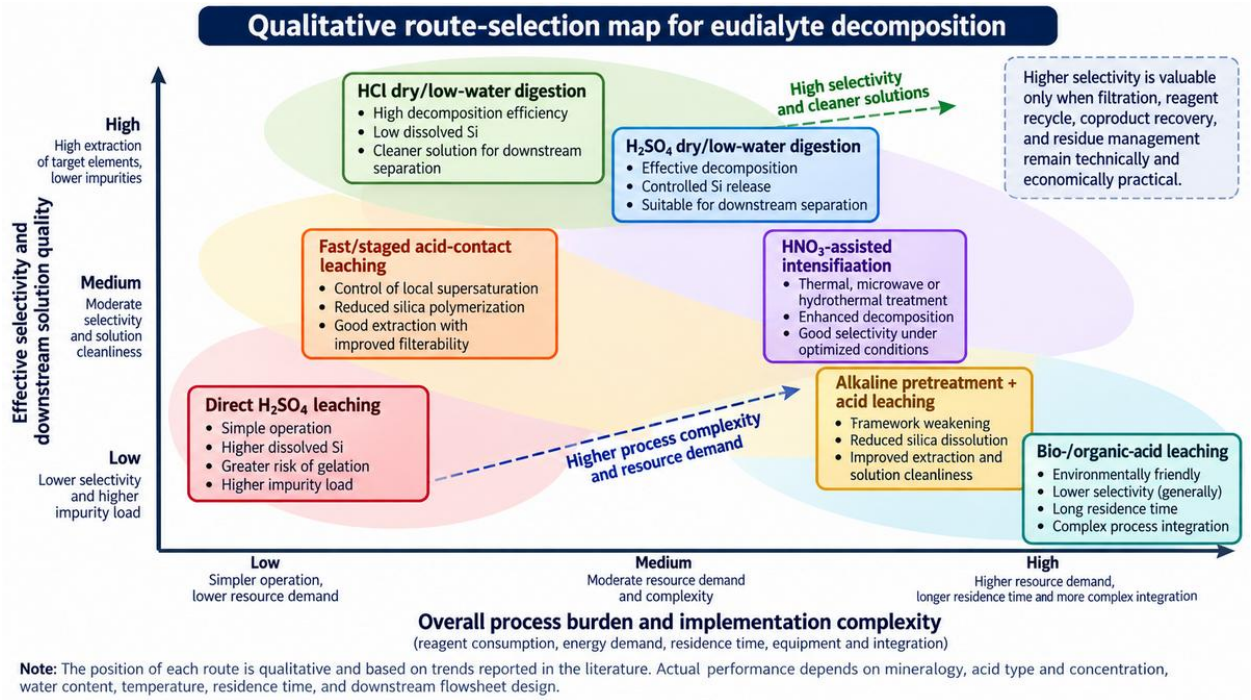

Figure 3

Conceptual route-selection map for eudialyte decomposition

Note. Original critical synthesis. Positioning is qualitative and reflects combined selectivity, silica control, process intensity, and downstream burden rather than a numerical ranking.

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7. Process intensification and alternative leaching

A substantial research program has examined mechanical, electrochemical, electromagnetic, ultrasonic, and combined energy inputs to accelerate eudialyte decomposition and improve Zr/REE recovery. The mechanistic rationale includes microcracking, surface activation, enhanced mass transfer, and modified reaction interfaces, each of which can shorten residence time or increase extraction at a given acid severity. Reported work spans mechanistic studies, nitric-acid optimization, recovery from pregnant solutions, and integrated processing concepts (Chanturia et al., 2017, 2019, 2020, 2021; Chanturiya, 2022; Chanturiya et al., 2021, 2022, 2023, 2024).

The critical scale-up question is energy productivity, not extraction improvement alone. Intensification is valuable only if the incremental energy demand is offset by lower acid consumption, smaller reactors, better filterability, higher product concentration, or improved overall recovery. Many laboratory studies report extraction gains without a complete electrical-energy balance, preventing direct comparison with low-water digestion routes. Future work should therefore report specific energy input (kWh t^{-1}), throughput, mixing power, residence time, and downstream filtration performance together.

Bioleaching provides a contrasting low-severity option. Experiments with zircon and eudialyte concentrates showed that eudialyte is more amenable to biological extraction than zircon, but chemical leaching at comparable acid concentrations can be similarly effective. Bioleaching should therefore be evaluated for low-grade, secondary, or niche feeds in which reaction time is less constraining, rather than assumed to replace high-throughput primary hydrometallurgy (Hedrich et al., 2023).

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8. Downstream REE separation and product formation

Once silicon is controlled, the PLS remains chemically complex. Fe, Al, Mn, Ca, Zr, Hf, Nb, Th, U, and variable alkali, sulfate, or chloride species can interfere with REE precipitation and solvent extraction. Effective downstream design therefore begins during leaching: a cleaner liquor can justify somewhat lower extraction if it materially reduces neutralization demand, sludge generation, or the number of solvent-extraction stages.

Precipitation remains a practical first concentration step. The EURARE-derived HCl route used controlled neutralization to remove major impurities before producing a mixed REE carbonate, demonstrating the value of converting a dilute, multicomponent liquor into a transportable intermediate (Ma et al., 2019a). Sulfuric-acid systems offer a different opportunity: in situ precipitation can transfer REEs into a solid phase while leaving other valuable components in solution, after which the REE-bearing phase can be redissolved under cleaner conditions (Balinski et al., 2020). This deliberate phase-transfer strategy can simplify separation by moving the target metals between solid and liquid phases under controlled conditions.

Sorption and ion exchange are increasingly relevant because they can separate metals without extensive bulk neutralization. Hypercrosslinked polystyrene sorbents have been investigated for Zr and REE recovery from nitric-acid leachates, whereas anion exchange can selectively recover Zr and Hf from sulfate solutions after REE extraction. These approaches demonstrate that eudialyte flowsheets need not end at mixed REE recovery: selective capture of other high-value components can materially improve the mass and revenue balance (Chanturia & Ryazantseva, 2024; Ma et al., 2019b).

Researchers have also studied specialty extractants for U, Th, and lanthanides in eudialyte concentrates. Such work remains relevant even when U and Th concentrations are low because

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regulatory and product-quality limits can be more stringent than metal-balance considerations. Selective removal of radioactive or penalty elements should therefore be designed as a product-specification step rather than treated only as environmental remediation (Safiulina et al., 2022, 2025).

Table 4 summarizes downstream operations by primary role, principal strengths, and critical control points. The practical sequence will be feed- and leachant-specific, but the general logic is robust: first control bulk impurities, then concentrate REEs, then perform fine separation or product finishing, while routing Zr–Hf–Nb to dedicated recovery where justified.

Table 4
Downstream separation and purification options after eudialyte decomposition

Downstream operation	Primary purpose	Strength	Critical control
Selective neutralization and precipitation	Remove Fe, Al, and Zr, or concentrate REEs	Simple, scalable, and compatible with carbonate products	pH window, REE loss, sludge mass, wash recovery
In situ REE precipitation	Separate REEs during leach sequence	Can improve liquor purity before solid-liquid separation	Solid phase identity, mother-liquor entrainment, re-dissolution
Ion exchange and sorption	Recover Zr-Hf or REEs from acidic media	High selectivity without bulk neutralization	Capacity, kinetics, regeneration, impurity competition
Solvent extraction	Fine REE or impurity separation	High selectivity with multistage contact	Acidity, phase disengagement, solvent loss, crud formation
Carbonate/oxalate finishing	Produce transportable REE intermediate	Established product form	Impurity specifications and washing

Note. Critical process synthesis based on Balinski et al. (2020), Chanturia and Ryazantseva (2024), Ma et al. (2019a, 2019b, 2020), and Safiulina et al. (2022, 2025).

9. Zr-Hf-Nb co-products, impurity control, and residue valorization

Eudialyte differs from many conventional REE minerals because Zr, Hf, Nb, Mn, and, in some deposits, other valuable elements can represent meaningful co-product potential. A REE-only

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flowsheet can therefore forfeit value by sending these elements to mixed neutralization sludge or to a residue without a defined recovery pathway. Consider sequential recovery from the start of route development (Balinski et al., 2019a; Chanturia et al., 2020; Ma et al., 2018a).

One integrated strategy is to extract REEs first while retaining much of the Zr–Hf–Nb in a silica-rich residue, and then apply a second, more selective digestion. Sulfuric-acid dry digestion with hydrogen peroxide promotion has been used to recover Zr, Hf, and Nb from post-REE eudialyte residue while limiting silicon dissolution. Subsequent ion exchange can enrich and separate Zr and Hf from sulfate media, and basic sulfate precipitation provides another purification option for zirconium (Ma et al., 2018a, 2019b, 2020; Pereira, 2026b). The sequence illustrates a general design principle: selective retention in the first stage can be advantageous when the retained phase is intentionally treated later.

Conversely, processes that dissolve all valuable components simultaneously face a more demanding separation problem. High overall dissolution does not necessarily constitute comprehensive recovery if co-products are lost during Fe/Al neutralization or if their concentrations are too low for economical separation. Mass balances should therefore track individual elements through the leach residue, wash liquor, impurity precipitate, REE product, and raffinate. Studies of rare-element losses during acid processing show how easily adsorption, coprecipitation, and entrainment can be overlooked when only solution extraction is reported (Balinski et al., 2019a; Lokshin et al., 2018).

10. Integrated flowsheets, pilot evidence, and scale-up constraints

The strongest process evidence connects decomposition to a downstream product rather than stopping at solution extraction. The HCl dry-digestion route, for example, was extended from laboratory optimization through impurity removal to pilot-scale production of an REE-carbonate

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intermediate, providing a more realistic measure of recovery than single-stage extraction. Other integrated programs have combined leaching, silica management, Zr/REE recovery, and process intensification, although the degree of pilot demonstration varies (Chanturia et al., 2024; Chanturiya, 2022; Ma et al., 2019a; Nechaev & Polyakov, 2025).

Figure 4 presents an integrated flowsheet concept distilled from the literature. Its central feature is the separation of the process into two coordinated value branches: an REE-liquor circuit and a Zr–Hf–Nb/residue circuit. Acid, water, and wash liquor are treated as internal process streams rather than as external utilities. This is essential because recycle changes ionic strength, silica polymerization, impurity build-up, and precipitation equilibria.

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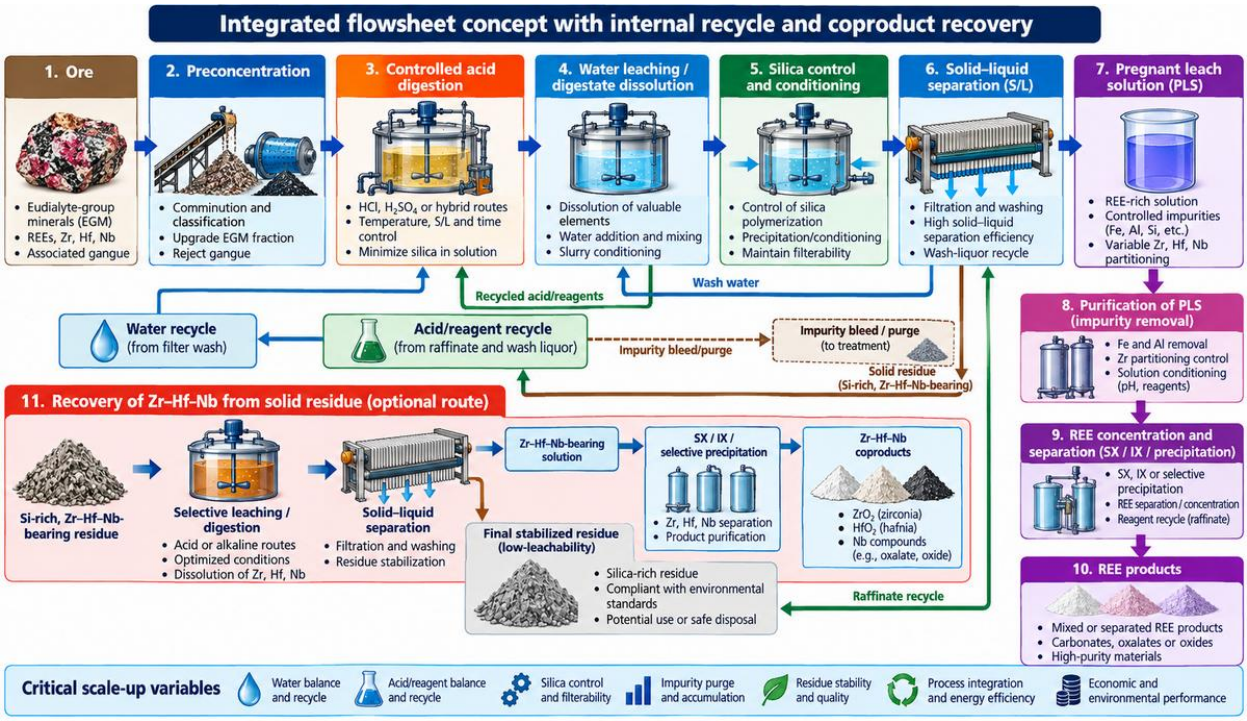

Figure 4

Integrated eudialyte flowsheet concept for REE and Zr–Hf–Nb recovery with internal recycle

Note. Original synthesis adapted from Balinski et al. (2020), Chanturiya (2022), Ma et al. (2018a, 2019a, 2019b, 2020), and Voßenkaul et al. (2017).

Scale-up is likely to fail at interfaces. Laboratory digestion can succeed but become nonuniform in larger reactors; a filterable cake at low pulp density can become compressible at industrial solids loading; washing can recover entrained REEs while diluting the liquor; and acid recycle can accumulate Ca, Na, sulfate, chloride, or silica until selectivity changes. These interactions mean that scale-up criteria should include mixing regime, heat release, water activity, cake resistance, wash efficiency, liquor density, impurity bleed, corrosion, and recycle stability.

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Mineral-processing scale-up is equally important. Variability in EGM grade, liberation, alteration, and gangue content changes both reagent consumption and residue mineralogy. Pilot campaigns should therefore process variability composites rather than a single "representative" concentrate. Without this step, a route optimized on a narrow feed may underestimate both acid demand and filtration risk (Nechaev & Polyakov, 2025; Silin et al., 2022; Stark et al., 2017).

11. Environmental performance, reagent recycling, and economic interpretation

Eudialyte is often presented as environmentally attractive because many occurrences contain comparatively low levels of U and Th relative to some monazite- or xenotime-bearing resources, and because heavy rare earth element (HREE)-rich mineralogy can alter the product-value distribution. Life-cycle studies have shown that a European eudialyte-based route can compare favorably with conventional reference chains for some REE products, particularly where HREE distribution and process integration are favorable. However, these conclusions are scenario-dependent and should not be generalized to all deposits or flowsheets (Schreiber et al., 2016; Zapp et al., 2018, 2022).

Acid manufacture, neutralization, water use, energy, and residue handling strongly influence environmental burden. A route that suppresses silica gel but uses large excesses of concentrated acid may transfer part of the burden from filtration to reagent production. Similarly, a flowsheet that maximizes REE recovery but discards Zr–Hf–Nb may be less resource-efficient than one that achieves slightly lower REE extraction while recovering co-products effectively. Comparative assessment should therefore use a functional basis that includes multiple products, together with system expansion or allocation rules appropriate to co-production (Schreiber et al., 2016; Talan & Huang, 2022; Zapp et al., 2022).

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Economic interpretation requires the same discipline. CAPEX and OPEX cannot be inferred from extraction percentages. Required inputs include acid consumption per tonne of concentrate, water-evaporation duty, reactor materials of construction, filtration area, washing demand, neutralizing reagent consumption, solvent or resin inventory, recycle losses, residue disposal, and product specifications. The most useful contribution of future techno-economic studies will be to identify the conditions under which co-product credits compensate for the comparatively low bulk REE grade of many eudialyte ores.

12. Knowledge gaps and research priorities

The literature is mature enough to identify the dominant mechanisms, but not mature enough to define a universally robust commercial process. Five gaps are particularly important. First, silica must be modeled as a kinetic and rheological process variable, not only as dissolved Si concentration. Measure polymerization rate, gel point, cake resistance, particle-size evolution, and metal adsorption under realistic pulp densities. Second, connect feed mineralogy quantitatively to reagent consumption and extraction through mineral-based mass balances rather than bulk assays alone.

Third, recycle remains underrepresented. Closed-loop acid and water systems will accumulate salts and impurities, changing activity coefficients and precipitation behavior. Recycle experiments should therefore run long enough to approach a quasi-steady composition, with explicit purge requirements. Fourth, co-product recovery requires a plant-wide objective function. Optimize REE, Zr, Hf, Nb, Mn, and impurity removal together because maximizing any one recovery can reduce total process value. Fifth, scale-up reporting requires common metrics: acid consumption (kg t^{-1} feed), fresh-water demand (m^3 t^{-1} feed), specific energy (kWh t^{-1}), PLS concentration, filter

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flux, cake moisture, washing efficiency, residue mass, and recovery to final product rather than extraction to solution.

Table 5 consolidates these priorities into a scale-up evidence framework. The central recommendation is to stop treating eudialyte hydrometallurgy as a search for a single "best leach." The more useful research question is which integrated operating window delivers stable filtration, concentrated and separable liquors, reagent recycle, co-product recovery, and compliant residues across realistic feed variability.

Table 5
Plant-relevant reporting metrics and evidence priorities for eudialyte process development

Scale-up topic	Minimum metric to report	Why it matters	Evidence priority
Silica and filtration	Dissolved Si, gel time, filter flux, cake moisture	Converts chemistry into operability	Very high
Reagent balance	kg acid and neutralizer t^{-1} concentrate	Dominates OPEX and environmental burden	Very high
Water balance	m^3 fresh water t^{-1} feed; recycle ratio; wash ratio	Controls liquor concentration and gelation	Very high
Energy intensification	kWh t^{-1} and residence-time reduction	Needed to justify energy-assisted methods	High
Product recovery	Recovery to final REE product and co-products	Avoids confusing extraction with saleable recovery	Very high
Recycle stability	Composition over repeated closed-loop cycles	Reveals impurity accumulation and selectivity drift	Very high
Residue quality	Mass, leachability, metal inventory, disposal/valorization route	Essential for permitting and resource efficiency	High

Note. Author synthesis from the critical gaps identified across the reviewed literature. "Evidence priority" refers to the importance of each metric for scale-up assessment, not to a ranking of specific technologies.

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13. Conclusions

Eudialyte-group minerals remain technically credible alternative resources for REEs and associated critical metals, but their processing advantage is conditional. Their acid reactivity enables comparatively mild decomposition, yet the same reaction releases silicon that can transform a chemically successful leach into an inoperable slurry. The most robust processing concepts therefore manage water activity and silicon speciation from the outset, using dry digestion, staged contact, controlled precipitation, or related strategies to maintain a filterable solid phase.

The evidence also shows that REE recovery should not be optimized in isolation. Zr, Hf, Nb, Mn, impurity removal, wash liquors, and residues are part of the same mass balance. Integrated recovery can improve resource efficiency and process economics, whereas indiscriminate dissolution can increase downstream complexity and forfeit co-product value. Process intensification and alternative leaching can widen the operating window, but evaluation should focus on specific energy, reagent use, throughput, and solid-liquid separation performance rather than extraction alone.

The decisive transition from laboratory success to industrial viability will depend on the coupled scale-up of reaction, filtration, recycle, and product purification. Future work should therefore report plant-relevant mass and water balances, repeated recycle cycles, filterability metrics, product specifications, and residue quality. Under this framework, eudialyte is best understood not as a single-mineral REE source, but as a multiproduct hydrometallurgical system whose viability depends on coordinated control of mineralogy, silica chemistry, phase separation, reagent and water recycle, co-product recovery, and residue quality.

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Conflict of Interest

The authors declare 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.

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References

Balinski, A., Atanasova, P., Wiche, O., Kelly, N., Reuter, M. A., & Scharf, C. (2019a). Recovery of REEs, Zr(+Hf), Mn and Nb by H_2SO_4 leaching of eudialyte concentrate. *Hydrometallurgy*, *186*, 176–186. https://doi.org/10.1016/j.hydromet.2019.04.007

Balinski, A., Atanasova, P., Wiche, O., Kelly, N., Reuter, M. A., & Scharf, C. (2019b). Selective leaching of rare earth elements (REEs) from eudialyte concentrate after sulfation and thermal decomposition of non-REE sulfates. *Minerals*, *9*(9), 522. https://doi.org/10.3390/min9090522

Balinski, A., Wiche, O., Kelly, N., Reuter, M. A., & Scharf, C. (2020). Separation of rare earth elements from contaminants and valuable components by in-situ precipitation during the hydrometallurgical processing of eudialyte concentrate. *Hydrometallurgy*, *194*, 105345. https://doi.org/10.1016/j.hydromet.2020.105345

Balomenos, E., Davris, P., Deady, E., Yang, J., Panias, D., Friedrich, B., Binnemans, K., Seisenbaeva, G., Dittrich, C., Kalvig, P., & Paspaliaris, I. (2017). The EURARE Project: Development of a sustainable exploitation scheme for Europe's rare earth ore deposits. *Johnson Matthey Technology Review*, *61*(2), 142–153. https://doi.org/10.1595/205651317X695172

Bogatyreva, E. V., Chub, A. V., Ermilov, A. G., & Khokhlova, O. V. (2018a). Efficiency of the alkaline-acid method of complex leaching of eudialyte concentrate. Part 2. Tsvetnye Metally, (8), 69–74. https://doi.org/10.17580/tsm.2018.08.09

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 18/09/2026 - **Accepted:** 04/11/2026
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DOI: 10.66104/9e78m554
Pages: 1-28

Bogatyreva, E. V., Khokhlova, O. V., Chub, A. V., & Ermilov, A. G. (2018b). The efficiency of the alkaline-acid method of complex leaching of eudialyte concentrate. Part 1. Tsvetnye Metally, (7), 57–61. https://doi.org/10.17580/tsm.2018.07.09

Bogatyreva, E. V., Khokhlova, O. V., Muraveva, E. A., & Dolgov, A. V. (2018c). Thermodynamic estimation of the probability of chemical reactions during alkaline decomposition of eudialyte concentrate. Tsvetnye Metally, (3), 46–56. https://doi.org/10.17580/tsm.2018.03.07

Borst, A. M., Finch, A. A., Friis, H., Horsburgh, N. J., Gamaletsos, P. N., Goettlicher, J., Steininger, R., & Geraki, K. (2020). Structural state of rare earth elements in eudialyte-group minerals. *Mineralogical Magazine*, *84*(1), 19–34. https://doi.org/10.1180/mgm.2019.50

Borst, A. M., Friis, H., Andersen, T., Nielsen, T. F. D., Waight, T. E., & Smit, M. A. (2016). Zirconosilicates in the kakortokites of the Ilímaussaq complex, South Greenland: Implications for fluid evolution and high-field-strength and rare-earth element mineralization in agpaitic systems. *Mineralogical Magazine*, *80*(1), 5–30. https://doi.org/10.1180/minmag.2016.080.046

Chanturia, V. A., Chanturia, E. L., Minenko, V. G., & Samusev, A. L. (2019). Acid leaching process intensification for eudialyte concentrate based on energy effects. Obogashchenie Rud, (3), 29–36. https://doi.org/10.17580/or.2019.03.05

Chanturia, V. A., Minenko, V. G., Kozhevnikov, G. A., & Samusev, A. L. (2024). Integrated processing technology for eudialyte concentrate. *Journal of Mining Science*, *60*(5), 841–853. https://doi.org/10.1134/S1062739124050144

Chanturia, V. A., Minenko, V. G., Samusev, A. L., Chanturia, E. L., & Koporulina, E. V. (2017). The mechanism of influence exerted by integrated energy impacts on intensified leaching of zirconium and rare earth elements from eudialyte concentrate. *Journal of Mining Science*, *53*(5), 890–896. https://doi.org/10.1134/S1062739117052921

Chanturia, V. A., Minenko, V. G., Samusev, A. L., Koporulina, E. V., & Ryazantseva, M. V. (2020). Zirconium and rare earths recovery from eudialyte concentrate leaching solution. *Journal of Mining Science*, *56*(4), 631–641. https://doi.org/10.1134/S1062739120046910

Chanturia, V. A., Nikolaev, A. I., & Aleksandrova, T. N. (2023). Innovative environmentally safe processes for the extraction of rare and rare-earth elements from complex ores of perplexed material composition. *Geology of Ore Deposits*, *65*, 425–437. https://doi.org/10.1134/S1075701523050045

Chanturia, V. A., & Ryazantseva, M. V. (2024). The use of hypercrosslinked polystyrene sorbents in extraction of valuable components from nitric acid leach solutions of eudialyte concentrate. *Journal of Mining Science*, *60*(3), 476–484. https://doi.org/10.1134/S1062739124030141

Chanturia, V. A., Samusev, A. L., Minenko, V. G., & Kozhevnikov, G. A. (2021). Rare metal and rare earth recovery from silica gel—Eudialyte concentrate leaching product. *Journal of Mining Science*, *57*(6), 1006–1013. https://doi.org/10.1134/S1062739121060132

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 18/09/2026 - **Accepted:** 04/11/2026
Vol: 01.06
DOI: 10.66104/9e78m554
Pages: 1-28

Chanturiya, V. A. (2022). Scientific substantiation and development of innovative processes for the extraction of zirconium and rare earth elements in the deep and comprehensive treatment of eudialyte concentrate. *Journal of Mining Institute*, *256*, 505–516. https://doi.org/10.31897/PMI.2022.31

Chanturiya, V. A., Minenko, V. G., Ryzanceva, M. V., & Samusev, A. L. (2024). Complex processing of eudialyte concentrate. Tsvetnye Metally, (12), 47–56. https://doi.org/10.17580/tsm.2024.12.05

Chanturiya, V. A., Minenko, V. G., Samusev, A. L., Chanturia, E. L., Koporulina, E. V., Bunin, I. Z., & Ryazantseva, M. V. (2021). The effect of energy impacts on the acid leaching of eudialyte concentrate. *Mineral Processing and Extractive Metallurgy Review*, *42*(7), 484–495. https://doi.org/10.1080/08827508.2020.1793141

Chanturiya, V. A., Minenko, V. G., Samusev, A. L., Koporulina, E. V., & Kozhevnikov, G. A. (2022). Physicochemical and energy impact on the process of leaching of a eudialyte concentrate. *Doklady Earth Sciences*, *505*(2), 534–542. https://doi.org/10.1134/S1028334X22080062

Chanturiya, V. A., Minenko, V. G., Samusev, A. L., Ryazantseva, M. V., & Koporulina, E. V. (2023). Combined physicochemical and energy methods to improve the recovery of rare earth elements from eudialyte concentrate. *Minerals*, *13*(3), 414. https://doi.org/10.3390/min13030414

Cheremisina, O. V., Volkova, O., & Litvinova, T. E. (2020). Influence of anion nature on acid leaching of silicate minerals and solvent extraction of rare and rare-earth elements. *Geochemistry*, *80*(3), 125507. https://doi.org/10.1016/j.chemer.2019.04.003

Davris, P., Stopic, S., Balomenos, E., Panias, D., Paspaliaris, I., & Friedrich, B. (2017). Leaching of rare earth elements from eudialyte concentrate by suppressing silica gel formation. *Minerals Engineering*, *108*, 115–122. https://doi.org/10.1016/j.mineng.2016.12.011

Goodenough, K. M., Schilling, J., Jonsson, E., Kalvig, P., Charles, N., Tuduri, J., Deady, E. A., Sadeghi, M., Schiellerup, H., Müller, A., Bertrand, G., Arvanitidis, N., Eliopoulos, D. G., Shaw, R. A., Thrane, K., & Keulen, N. (2016). Europe's rare earth element resource potential: An overview of REE metallogenetic provinces and their geodynamic setting. *Ore Geology Reviews*, *72*, 838–856. https://doi.org/10.1016/j.oregeorev.2015.09.019

Hedrich, S., Breuker, A., Martin, M., & Schippers, A. (2023). Rare earth elements (bio)leaching from zircon and eudialyte concentrates. *Hydrometallurgy*, *219*, 106068. https://doi.org/10.1016/j.hydromet.2023.106068

Kogarko, L. N. (2023). Rare earth element resource potential of super-large deposits in Eastern Fennoscandia. *Doklady Earth Sciences*, *513*, 1296–1300. https://doi.org/10.1134/S1028334X23602067

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 18/09/2026 - **Accepted:** 04/11/2026
Vol: 01.06
DOI: 10.66104/9e78m554
Pages: 1-28

Kogarko, L. N., & Nielsen, T. F. D. (2020). Chemical composition and petrogenetic implications of eudialyte-group mineral in the peralkaline Lovozero Complex, Kola Peninsula, Russia. *Minerals*, *10*(11), 1036. https://doi.org/10.3390/min10111036

Kogarko, L. N., & Nielsen, T. F. D. (2021). Compositional variation of eudialyte-group minerals from the Lovozero and Ilímaussaq complexes and on the origin of peralkaline systems. *Minerals*, *11*(6), 548. https://doi.org/10.3390/min11060548

Lokshin, E. P., Elizarova, I. R., Ryskina, M. P., & Tareeva, O. A. (2018). On the composition of eudialyte concentrate. Tsvetnye Metally, (2), 10–14. https://doi.org/10.17580/tsm.2018.02.01

Lokshin, E. P., & Tareeva, O. A. (2020). Decomposition of an eudialyte concentrate with nitric acid by sorption conversion. *Russian Metallurgy (Metally)*, *2020*(9), 964–970. https://doi.org/10.1134/S0036029520090086

Lokshin, E. P., Tareeva, O. A., & Drogobuzhskaya, S. V. (2020). Study of the decomposition of eudialyte concentrate by means of sorption conversion in sulphuric medium. *Chemistry for Sustainable Development*, *28*, 174–179. https://doi.org/10.15372/CSD2020217

Lokshin, E. P., Tareeva, O. A., & Drogobuzhskaya, S. V. (2022). Sorption conversion of eudialyte concentrate in sulphuric acid medium. *Chemistry for Sustainable Development*, *30*(3), 266–272. https://doi.org/10.15372/CSD2022381

Lokshin, E. P., Tareeva, O. A., & Drogobuzhskaya, S. V. (2023). Decomposition of an eudialyte concentrate by sorption conversion in nitric and hydrochloric acid media. *Russian Metallurgy (Metally)*, *2023*(3), 340–346. https://doi.org/10.1134/S0036029523030096

Lokshin, E. P., Tareeva, O. A., & Elizarova, I. R. (2018). On the subject of losses of rare elements in acid processing of eudialyte concentrate. *Chemistry for Sustainable Development*, *26*(2), 155–161. https://doi.org/10.15372/CSD20180207

Ma, Y., Stopic, S. R., & Friedrich, B. G. (2017). Leaching of eudialyte concentrate and REE-precipitation. In Proceedings of the 9th European Metallurgical Conference, EMC 2017 (Vol. 2, pp. 595–600).

Ma, Y., Stopic, S., & Friedrich, B. (2019a). Hydrometallurgical treatment of an eudialyte concentrate for preparation of rare earth carbonate. *Johnson Matthey Technology Review*, *63*(1), 2–13. https://doi.org/10.1595/205651318X15270000571362

Ma, Y., Stopic, S., Gronen, L., & Friedrich, B. (2018a). Recovery of Zr, Hf, Nb from eudialyte residue by sulfuric acid dry digestion and water leaching with H_2O_2 as a promoter. *Hydrometallurgy*, *181*, 206–214. https://doi.org/10.1016/j.hydromet.2018.10.002

Ma, Y., Stopic, S., Gronen, L., Milivojevic, M., Obradovic, S., & Friedrich, B. (2018b). Neural network modeling for the extraction of rare earth elements from eudialyte concentrate by dry digestion and leaching. *Metals*, *8*(4), 267. https://doi.org/10.3390/met8040267

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 18/09/2026 - **Accepted:** 04/11/2026
Vol: 01.06
DOI: 10.66104/9e78m554
Pages: 1-28

Ma, Y., Stopic, S., Huang, Z., & Friedrich, B. (2019b). Selective recovery and separation of Zr and Hf from sulfuric acid leach solution using anion exchange resin. *Hydrometallurgy*, *189*, 105143. https://doi.org/10.1016/j.hydromet.2019.105143

Ma, Y., Stopic, S., Wang, X., Forsberg, K., Friedrich, B., & Schreiner, C. (2020). Basic sulfate precipitation of zirconium from sulfuric acid leach solution. *Metals*, *10*(8), 1099. https://doi.org/10.3390/met10081099

Matveev, V. A., Mayorov, D. V., & Solovev, A. V. (2018). Integrated technology of sulfuric acid treatment for eudialyte concentrate. Tsvetnye Metally, (1), 20–27. https://doi.org/10.17580/tsm.2018.01.02

Mikhailova, J. A., Pakhomovsky, Y. A., Kalashnikova, G. O., & Aksenov, S. M. (2022a). Dissolution of the eudialyte-group minerals: Experimental modeling of natural processes. *Minerals*, *12*(11), 1460. https://doi.org/10.3390/min12111460

Mikhailova, J. A., Pakhomovsky, Y. A., Panikorovskii, T. L., Bazai, A. V., & Yakovenchuk, V. N. (2020). Eudialyte group minerals from the Lovozero Alkaline Massif, Russia: Occurrence, chemical composition, and petrogenetic significance. *Minerals*, *10*(12), 1070. https://doi.org/10.3390/min10121070

Mikhailova, J. A., Stepenshchikov, D. G., Kalashnikov, A. O., & Aksenov, S. M. (2022b). Who is who in the eudialyte group: A new algorithm for the express allocation of a mineral name based on the chemical composition. *Minerals*, *12*(2), 224. https://doi.org/10.3390/min12020224

Nechaev, A. V., & Polyakov, E. G. (2025). Problems of chemical technology of eudialyte and ways to solve them. *Theoretical Foundations of Chemical Engineering*, *59*(1), 125–132. https://doi.org/10.1134/S004057952570023X

Panikorovskii, T. L., Mikhailova, J. A., Pakhomovsky, Y. A., Bazai, A. V., Aksenov, S. M., Kalashnikov, A. O., & Krivovichev, S. V. (2021). Zr-rich eudialyte from the Lovozero Peralkaline Massif, Kola Peninsula, Russia. *Minerals*, *11*(9), 982. https://doi.org/10.3390/min11090982

Pereira, A. C. (2025). Processing technologies for rare earth elements from peralkaline igneous deposits: A systematic review. *REMUNOM, 21*(2), 1–44. https://doi.org/10.61164/p8v9aq27

Pereira, A. C. (2026a). Brazil's rare earth elements landscape: From geological endowment to mine-to-magnet integration—Operations, resources, bottlenecks, market prospects, and research gaps. *Nexus Science Review, 1*(4). https://doi.org/10.66104/7tpw1x21

Pereira, A. C. (2026b). Recovery of zirconium from primary and secondary resources: Chemistry, Zr/Hf separation, electrochemical routes, and industrial perspectives. *Journal International Review of Research Studies, 1*(9), 1–58. https://doi.org/10.66104/s3mdb246

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 18/09/2026 - **Accepted:** 04/11/2026
Vol: 01.06
DOI: 10.66104/9e78m554
Pages: 1-28

Pfaff, K., Wenzel, T., Schilling, J., Marks, M. A. W., & Markl, G. (2010). A fast and easy-to-use approach to cation site assignment for eudialyte-group minerals. *Neues Jahrbuch für Mineralogie – Abhandlungen*, *187*(1), 69–81. https://doi.org/10.1127/0077-7757/2010/0166

Rastsvetaeva, R. K., & Chukanov, N. V. (2012). Classification of eudialyte-group minerals. *Geology of Ore Deposits*, *54*(7), 487–497. https://doi.org/10.1134/S1075701512070069

Rastsvetaeva, R. K., & Chukanov, N. V. (2020). New data on the isomorphism in eudialyte-group minerals. 2. Crystal-chemical mechanisms of blocky isomorphism at the key sites. *Minerals*, *10*(8), 720. https://doi.org/10.3390/min10080720

Safiulina, A. M., Lizunov, A. V., Ivanov, A. V., Borisova, N. E., Matveev, P. I., Aksenov, S. M., & Ivanets, D. V. (2025). Uranium(VI), thorium(IV), and lanthanides(III) extraction from the eudialyte concentrate using the N, O-hybrid heterocyclic reagents. *Metals*, *15*(5), 494. https://doi.org/10.3390/met15050494

Safiulina, A. M., Lizunov, A. V., Semenov, A. A., Baulin, D. V., Baulin, V. E., Tsivadze, A. Y., Aksenov, S. M., & Tananaev, I. G. (2022). Recovery of uranium, thorium, and other rare metals from eudialyte concentrate by a binary extractant based on 1,5-bis[2-(hydroxyethoxyphosphoryl)-4-ethylphenoxy]-3-oxapentane and methyl trioctylammonium nitrate. *Minerals*, *12*(11), 1469. https://doi.org/10.3390/min12111469

Schilling, J., Wu, F.-Y., McCammon, C., Wenzel, T., Marks, M. A. W., Pfaff, K., Jacob, D. E., & Markl, G. (2011). The compositional variability of eudialyte-group minerals. *Mineralogical Magazine*, *75*(1), 87–115. https://doi.org/10.1180/minmag.2011.075.1.87

Schreiber, A., Marx, J., Zapp, P., Hake, J.-F., Voßenkaul, D., & Friedrich, B. (2016). Environmental impacts of rare earth mining and separation based on eudialyte: A new European way. *Resources*, *5*(4), 32. https://doi.org/10.3390/resources5040032

Silin, I., Dertmann, C., Cvetković, V. S., Stopic, S., & Friedrich, B. (2024). Prevention of silica gel formation for eudialyte study using a new digestion reactor. *Minerals*, *14*(2), 124. https://doi.org/10.3390/min14020124

Silin, I., Gürsel, D., Büchter, C., Weitkämper, L., & Wotruba, H. (2022). Recovery of catapleiite and eudialyte from the non-magnetic fraction of eudialyte ore processing of the Norra Kärr deposit. *Minerals*, *12*(1), 19. https://doi.org/10.3390/min12010019

Sjöqvist, A. S. L., Cornell, D. H., Andersen, T., Erambert, M., Ek, M., & Leijd, M. (2013). Three compositional varieties of rare-earth element ore: Eudialyte-group minerals from the Norra Kärr Alkaline Complex, southern Sweden. *Minerals*, *3*(1), 94–120. https://doi.org/10.3390/min3010094

Sjöqvist, A. S. L., Cornell, D. H., Andersen, T., Erambert, M., Ek, M., & Leijd, M. (2020). Modification of a rare-earth element deposit by low-temperature partial melting during metamorphic

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Pages: 1-28

overprinting: Norra Kärr alkaline complex, southern Sweden. *Chemical Geology*, *545*, 119640. https://doi.org/10.1016/j.chemgeo.2020.119640

Stark, T., Silin, I., & Wotruba, H. (2017). Mineral processing of eudialyte ore from Norra Kärr. *Journal of Sustainable Metallurgy*, *3*(1), 32–38. https://doi.org/10.1007/s40831-016-0073-5

Talan, D., & Huang, Q. (2022). A review of environmental aspect of rare earth element extraction processes and solution purification techniques. *Minerals Engineering*, *179*, 107430. https://doi.org/10.1016/j.mineng.2022.107430

van de Ven, M. A. J., Borst, A. M., Davies, G. R., Hunt, E. J., & Finch, A. A. (2019). Hydrothermal alteration of eudialyte-hosted critical metal deposits: Fluid source and implications for deposit grade. *Minerals*, *9*(7), 422. https://doi.org/10.3390/min9070422

Voßenkaul, D., Birich, A., Müller, N., Stoltz, N., & Friedrich, B. (2017). Hydrometallurgical processing of eudialyte bearing concentrates to recover rare earth elements via low-temperature dry digestion to prevent the silica gel formation. *Journal of Sustainable Metallurgy*, *3*(1), 79–89. https://doi.org/10.1007/s40831-016-0084-2

Zapp, P., Marx, J., Schreiber, A., Friedrich, B., & Voßenkaul, D. (2018). Comparison of dysprosium production from different resources by life cycle assessment. *Resources, Conservation and Recycling*, *130*, 248–259. https://doi.org/10.1016/j.resconrec.2017.12.006

Zapp, P., Schreiber, A., Marx, J., & Kuckshinrichs, W. (2022). Environmental impacts of rare earth production. *MRS Bulletin*, *47*, 267–275. https://doi.org/10.1557/s43577-022-00286-6