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Brazil's Rare Earth Elements Landscape: From Geological Endowment to Mine-to-Magnet Integration—Operations, Resources, Bottlenecks, Market Prospects, and Research Gaps

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Abstract

Brazil has re-emerged as one of the most consequential rare-earth jurisdictions outside Asia, but geological scale alone does not determine whether it can capture strategic and economic value from rare earth elements (REEs). This structured critical review evaluates Brazil's REE landscape from 2020 through 9 September 2026 using a mine-to-magnet framework that integrates geology, mineralogy, beneficiation, extraction, impurity control, separation, environmental performance, economics, policy, recycling, and downstream manufacturing. We screened an initial contemporary evidence pool of 150 records; we retained 60 sources, complemented by six foundational pre-2020 works. Evidence types are explicitly separated between peer-reviewed mechanistic evidence and dated government, technical, institutional, and company project-status sources, and all fast-moving project, policy, and market claims are frozen at the review cut-off date. The analysis introduces the Resource-to-Value Gap (R2V Gap) to distinguish geological abundance from the capability to deliver selectively recoverable, specification-compliant, and commercially secure products. It also proposes a five-level REE project-readiness scale (TRL-REE) and the Brazilian REE Value-Chain Readiness (BREE-VCR) framework to compare projects beyond resource tonnage and total rare-earth-oxide (TREO) grade. Serra Verde demonstrates that Brazilian ionic-regolith resources can reach commercial production, whereas Caldeira, Colossus, Carina, and Araxá illustrate a rapidly advancing pipeline with distinct mineralogical, metallurgical, product, and execution risks. The principal bottleneck is increasingly located after mixed-product generation, where purification, individual REE separation, magnet-grade oxide qualification, metals and alloys, and industrial magnet manufacturing determine value capture. Closing the R2V Gap therefore requires staged integration of competitive primary production, domestic separation capability, international offtake, targeted magnet manufacturing, recycling, and auditable industrial policy.

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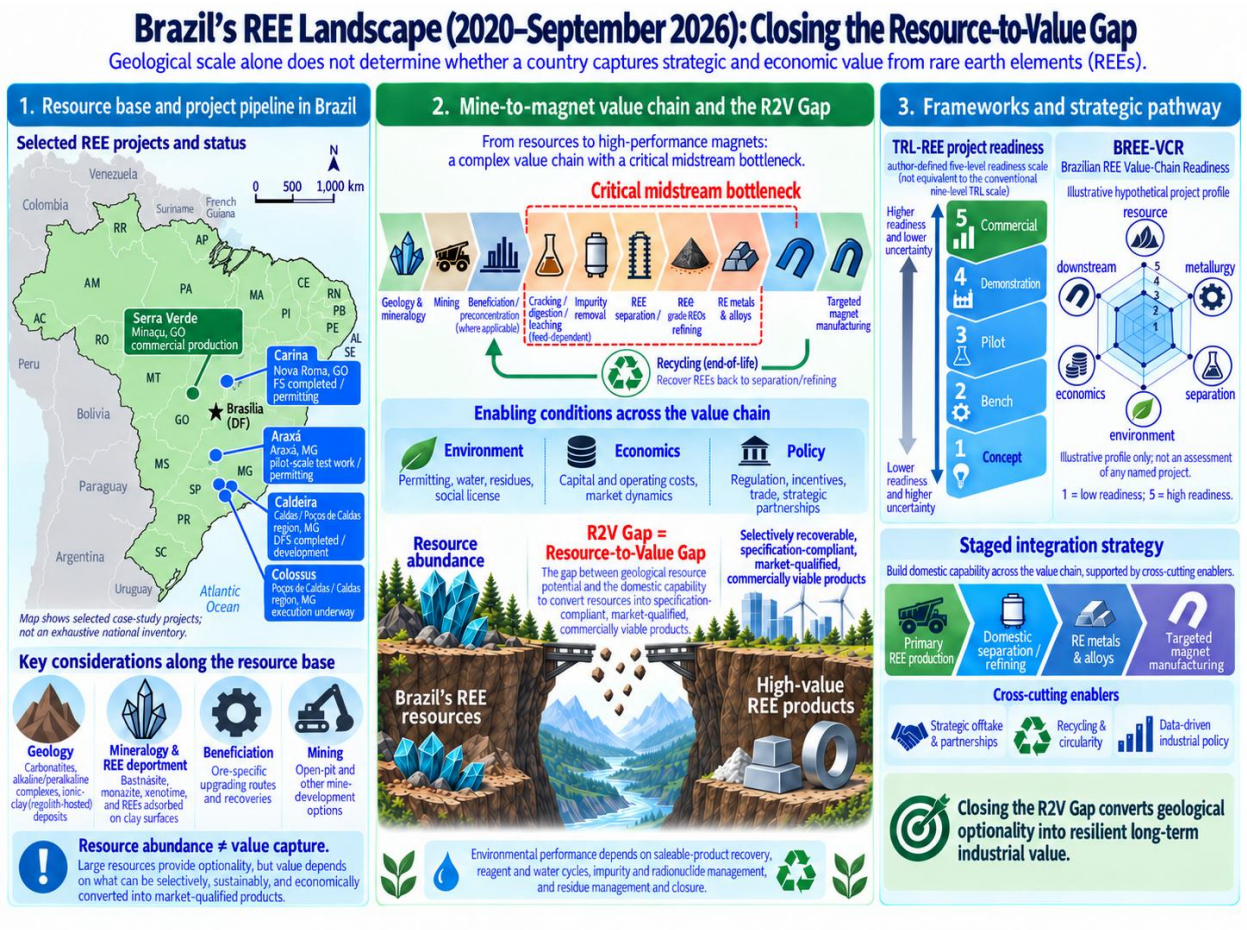
Keywords: Rare earth elements; Brazil; ionic adsorption clays; critical minerals; rare-earth separation; permanent magnets

Highlights

- Brazil combines world-scale REE geological endowment with a rapidly emerging portfolio of ionic-clay and hard-rock projects.
- The principal strategic bottleneck is shifting from resource discovery toward selective extraction, separation, refining, and magnet-grade product manufacture.
- Resource tonnage and TREO grade alone are insufficient indicators of project quality; recoverability and Nd–Pr–Dy–Tb basket value are more informative.
- Closing Brazil's Resource-to-Value Gap requires coordinated advances in metallurgy, separation, financing, policy, recycling, and downstream manufacturing.Graphical abstract



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1. Introduction: Brazil in the Emerging Global REE Supply Landscape

1.1. Rare earths and the restructuring of global critical-mineral supply chains

Rare earth elements occupy an unusual position in critical-mineral policy: geological occurrences are widespread, but mine supply, chemical separation, metal/alloy production, and permanent-magnet manufacturing are geographically concentrated. This concentration transforms what might appear to be a conventional mining problem into a coupled challenge spanning mineral processing, chemical separations, product qualification, industrial know-how, and market coordination. The strongest demand signal comes from high-performance neodymium-iron-boron (NdFeB) permanent magnets, for which Nd and Pr provide the principal magnetic phase and Dy and Tb are strategically important for high-temperature coercivity. Supply-chain resilience therefore cannot be assessed from total rare-earth-oxide (REO) production alone; it must be evaluated at the level of individual elements, product purity, conversion capacity, and end-use qualification (Alonso et al., 2012; Bogmans et al., 2026; Gutfleisch et al., 2011; Guo & Wang, 2024; Heim & Vander Wal, 2023; Ilankoon et al., 2022; International Energy Agency, 2026; Zuo et al., 2022).

1.2. Why Brazil has re-emerged as a strategic REE jurisdiction

Brazil combines unusually diverse primary and secondary REE occurrences with established mining infrastructure, a large share of renewable electricity, mature mineral-processing capabilities, and a rapidly expanding project pipeline. National geological assessments identify ionic/regolith-hosted systems, alkaline-carbonatite complexes, granitic and peralkaline systems, monazite-bearing placers, and opportunities associated with niobium, phosphate, tin, and historical mineral residues (Cunha et al., 2025; Santana & Botelho, 2022). The decisive change during the review window was the transition from geological potential to current production: Serra Verde entered commercial production at Pela Ema in early 2024, providing Brazil with a modern

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reference case for large-scale recovery of the four principal magnet REEs from an ionic-clay-type deposit (Serra Verde Group, 2024; Agência Nacional de Mineração, 2025).

1.3. The contradiction between geological endowment and industrial output

The central paradox is simple yet analytically important: a large geological endowment does not imply a large integrated REE industry. The discrepancy is evident even in headline reserve statistics. The 2025 Brazilian Mineral Summary reports 11.4 Mt of proved-plus-probable REE reserves for the 2024 base year, whereas the 2026 U.S. Geological Survey summary lists 21 Mt of Brazilian reserves and mine production of about 560 t REO in 2024 and 2,000 t in 2025 (Agência Nacional de Mineração, 2025; U.S. Geological Survey, 2026). These figures should not be treated as equivalent. They reflect different reporting dates, data revisions, national classification rules, and aggregation procedures. The analytical task is therefore to reconcile definitions and evidence quality before comparing Brazil internationally.

1.4. Limitations of previous Brazil-focused REE assessments

Earlier assessments have been indispensable for describing occurrences, metallogenic provinces, mineralogical systems, and the geopolitical relevance of Brazilian REEs. However, geology-first assessments can overstate strategic readiness when in-ground inventory is treated as a proxy for industrial capability. A second limitation is the tendency to compare projects primarily by resource tonnes or TREO grade, even though desorbable fraction, mineral deportment, impurity burden, magnet-REE distribution, product recovery, and downstream separation strongly affect value. A third limitation is treating processing, environmental, social, and governance (ESG) performance, policy, and downstream manufacturing as separate domains rather than sequential constraints within a single value chain (Collerson et al., 2025; Huang & Xie, 2025; Mindreau, 2025).

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This review refers to the resource-determinism fallacy as the assumption that a large in-ground inventory, high TREO grade, or favorable country ranking can be interpreted directly as industrial or strategic capability. That inference fails whenever geological inventory is weakly linked to desorbable or liberated REE, selective recovery, impurity control, saleable-product specification, permitting, financing, offtake, or downstream conversion. The analytical unit used here is therefore not geological abundance alone, but the fraction of geological value that survives each technical and institutional transition to a qualified product.

1.5. Scope, objectives, and critical questions of this review

This review spans January 2020 through 9 September 2026 and poses a more demanding question than whether Brazil "has" rare earths: can Brazil convert its heterogeneous REE endowment into selectively recoverable, separable, specification-compliant, environmentally defensible, and commercially secure products? Three linked analytical tools organize the answer. The Resource-to-Value Gap (R2V Gap) defines the problem by identifying technical, economic, institutional, and market losses between geological endowment and qualified end-use products. TRL-REE classifies the maturity of project evidence from occurrence to commercial operation. BREE-VCR organizes value-chain readiness across geology, resource quality, metallurgy, separation, ESG, infrastructure, financing, offtake, and downstream integration. The review traces the chain from resource quality through mining, pre-concentration, hydrometallurgical extraction, mixed rare-earth carbonate (MREC) or mixed oxide, individual REE separation, oxide finishing, metals/alloys, NdFeB magnets, end-use qualification, and recycling. The framework deliberately shifts the unit of analysis from "ore in the ground" to recoverable and saleable value at product specification.

The reserve and production figures that frame this paradox are reconciled in Table 1. Table 1 is intentionally organized by reporting milestone rather than as a continuous statistical series

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because Brazilian and international sources do not use identical reserve definitions or revision schedules (Agência Nacional de Mineração, 2025; U.S. Geological Survey, 2026).

Table 1. *Selected milestones in the evolution and reconciliation of Brazilian REE reserves, production, and industrial status, 2020–2026*

Reporting milestone	Reserve/resource signal	Production/operating signal	Critical interpretation
2020–2023	Large, diverse geological potential; multiple regolith, carbonatite, granite and placer systems	No modern-scale mine-to-magnet chain	Resource potential dominated the narrative; industrial conversion remained limited.
ANM 2025 (base year 2024)	11.4 Mt proved + probable reserves	Serra Verde start-up described as the main new beneficiated production	National reserve number is tied to ANM classification and 2024 base-year reporting.
USGS 2026 (2024 revised)	21 Mt reserves in the 2026 summary	560 t REO mine production for 2024	USGS revised Brazilian data; do not substitute the reserve figure mechanically for ANM's national category.
USGS 2026 (2025 estimate)	21 Mt reserves carried in the 2026 summary	2,000 t REO mine production for 2025	Production growth is material but remains small relative to geological endowment.
2026 project/policy acceleration	Large advanced resources at Caldeira, Colossus, Carina and Araxá	Serra Verde operating; multiple projects in feasibility/definitive-feasibility, pilot, or permitting stages	The bottleneck is shifting from discovery to selective metallurgy, separation, finance, and downstream integration.

Note. Evidence summary synthesized from Agência Nacional de Mineração (2025), U.S. Geological Survey (2026), Serra Verde Group (2024), and the project sources reviewed here. Reserve figures are not treated as directly interchangeable across reporting systems.

Table 1 shows why a critical review must preserve each number's provenance. The apparent "reserve gap" between 11.4 and 21 Mt is not evidence that one institution is necessarily wrong; it warns that country rankings can become misleading when category, effective date, and revision methodology are stripped from the data. This distinction becomes even more important when corporate mineral resources, ore reserves, contained TREO, and desorbable REE are compared in the same table.

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2. Review Methodology and Evidence-Assessment Framework

2.1. Literature-search strategy and review window

The review was designed as a structured critical synthesis rather than a PRISMA systematic review or meta-analysis. The contemporary evidence search used a master Brazilian REE equation and domain-specific Boolean combinations covering resources/reserves, deposit diversity, ionic-regolith systems, mineralogy/deportment, beneficiation, leaching, impurity co-dissolution, separation/refining, Nd-Pr-Dy-Tb basket quality, economics/bankability, policy, recycling, mine-to-magnet integration, and the principal Brazilian project pipeline. The equations were prepared in forms transferable to Google Scholar and field-tagged bibliographic databases; Appendix A. 1 reproduces the core equations verbatim so the thematic search can be repeated. Targeted retrieval of project and policy evidence additionally used primary government, institutional, technical, and company sources because time-sensitive project milestones are often not yet represented in journal databases. An initial working pool of 150 contemporary records was screened and 60 sources were retained in the 2020-9 September 2026 synthesis; six pre-2020 foundational works were then added only to anchor canonical beneficiation, solvent-extraction, magnet, recycling, resource-reporting, and critical-mineral concepts. The final cited corpus therefore contains 66 sources. Historical query-level retrieval logs were not preserved prospectively, so database-specific record counts and numerical exclusion subcounts are not reconstructed retrospectively; corpus-level screening counts and final source-type counts are reported transparently in Appendix Tables S1 and S2.

Duplicates were identified using DOI where available and by normalized title plus author-year matching when a DOI was absent. For project and policy records, we replaced superseded releases with the most recent relevant source available before the cut-off. Inclusion required direct relevance to at least one review domain, traceable bibliographic or institutional metadata, and sufficient evidence to support the specific claim type. The principal date window was January

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2020 through 9 September 2026; earlier sources were eligible only when they provided foundational concepts not adequately replaced by recent literature. Exclusion criteria were duplicate or superseded records, peripheral REE mentions without analytical relevance, non-traceable claims, opinion/promotional material lacking a usable primary evidence basis, and sources whose information was already represented by a more complete or more recent source. The aggregate difference between the 150-record working pool and the 60-source contemporary corpus is reported as 90 records not retained; because reason-specific historical counts were not archived, no artificial retrospective allocation of those 90 records is presented.

2.2. Scientific literature, government databases, and company disclosures

We matched evidence type to claim type because the fastest-moving Brazilian projects are not yet fully represented in the journal literature. The final 66-source corpus comprises 49 peer-reviewed scientific sources, five government/statistical sources, two technical/reporting-standard sources, five company disclosures, and five institutional or policy-oriented reports. Peer-reviewed literature was preferentially used for geological, mineralogical, hydrometallurgical, separation, environmental, and mechanistic claims. Government and statistical sources were used for official reserve, production, regulatory, and policy statements. Project-specific development status, resource updates, feasibility milestones, pilot results, planned capacities, and offtake information were taken from dated primary technical or corporate disclosures when journal evidence was unavailable. These corporate sources were treated as project-status evidence rather than independent scientific verification. Appendix Table S4 records disclosure date, study or reporting basis, and the due-diligence boundary used for Serra Verde, Caldeira, Colossus, Carina, and Araxá. The source hierarchy and claim-to-source mapping are summarized in Appendix Tables S2 and S3.

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2.3. Resource-versus-reserve terminology

The terms resource, reserve, contained TREO, ore reserve, desorbable REE, and product recovery are not interchangeable. A mineral resource is a geological-economic estimate with specified confidence, whereas an ore reserve incorporates modifying factors and economic extraction assumptions. For ionic-clay systems, a further distinction is required between total assay and exchangeable or desorbable REE, because only a fraction of the measured total may be accessible under mild salt leaching. For hard-rock ores, mineral locking, liberation, cracking requirements, radionuclide deportment, and impurity dissolution similarly determine how much geological inventory can enter a marketable product (Bishop et al., 2024; Collerson et al., 2025; Joint Ore Reserves Committee, 2012; Ding & Azimi, 2024; He et al., 2023; Russo et al., 2025; Villanova-de-Benavent et al., 2026; Wu et al., 2023).

2.4. Evidence quality and the proposed TRL-REE classification

To make project comparisons transparent, this review proposes a five-level REE-specific readiness classification. TRL-REE 1 corresponds to geological occurrence; TRL-REE 2 to a defined mineral resource; TRL-REE 3 to metallurgically demonstrated recovery at a meaningful test scale; TRL-REE 4 to feasibility, permitting, and/or integrated pilot-demonstration maturity; and TRL-REE 5 to commercial production. The scale is intentionally simpler than conventional technology-readiness systems used in R&D and is used only to organize the maturity of publicly available evidence. Project positions were assigned by the author from the dated evidence summarized in this review; independent duplicate scoring and inter-rater reliability were not performed. Consequently, TRL-REE and the associated project-readiness map are explicitly heuristic, date-bound judgments rather than validated ratings. A project can have a very large resource while remaining at a lower TRL-REE level if selective recovery, product quality, residue closure, permitting, financing, or sustained operation remains insufficiently demonstrated.

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Caution - scope of TRL-REE. TRL-REE is an analytical screening tool for evidentiary maturity. It is not a JORC or NI 43-101 reporting category, Mineral Resource or Ore Reserve classification, feasibility conclusion, investment rating, valuation model, or substitute for independent technical due diligence.

2.5. Chain boundaries, critical synthesis metrics, and data cut-off

The mine-to-magnet chain is defined explicitly to avoid ambiguity in the terms upstream, midstream, and downstream. Upstream comprises resource definition, mining, and physical pre-concentration. Hydrometallurgical extraction includes leaching/desorption, impurity control, and production of MREC or mixed oxide. Midstream covers individual REE separation, purification, and oxide finishing to customer specification. Downstream comprises oxide-to-metal conversion, alloy production, NdFeB magnet manufacturing, component qualification, and end-use integration. Recycling is a cross-cutting secondary loop that can re-enter the chain at the concentrate, separated compound, metal/alloy, or direct-reuse stages. Three analytical rules were then applied throughout: resource size and TREO grade are necessary but insufficient descriptors; extraction must be distinguished from selectivity because Fe, Al, Ca, Mg, P, Th, U, or silica co-dissolution can worsen the full flowsheet; and value is evaluated at a defined saleable-product boundary. These rules motivate RBV in Section 10 and the BREE-VCR matrix in Section 12. Together with TRL-REE and the R2V Gap, they provide a consistent language for comparing projects that disclose different types of evidence.

Data cut-off and update policy. All project capacities, resource/reserve statements, feasibility and permitting milestones, offtake arrangements, policy status, production targets, and market-sensitive development claims were frozen at 9 September 2026. Later changes are outside the temporal boundary of this review. The review does not independently verify company Mineral Resource or Ore Reserve statements beyond the cited public documents and should not be interpreted as investment advice, project valuation, or a recommendation to transact in any security or project.

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3. Global REE Market and Brazil's Strategic Position

3.1. Mine production, reserves, and supply-chain concentration

Global REE supply remains characterized by a mismatch between dispersed geology and concentrated industrial conversion. Mine production has diversified gradually, but separation, metal/alloy production, and magnet manufacturing remain more concentrated than mining. This distinction matters because an upstream producer can still depend on external midstream processing, qualification, and price-setting mechanisms. Industry surveys and trade-network analyses show that diversification is constrained by capital intensity, technical know-how, market volatility, long qualification cycles, and the difficulty of coordinating mines with separation and magnet capacity (Bogmans et al., 2026; Guo & Wang, 2024; Ilankoon et al., 2022; International Energy Agency, 2026; Zuo et al., 2022). Brazil therefore enters the global system not as a blank-slate competitor, but as a potential upstream and midstream diversification node within an already highly structured market.

3.2. Magnet REEs versus bulk REEs

TREO aggregation conceals the elements that drive strategic value. La and Ce can dominate mass but have different price and demand dynamics from Nd, Pr, Dy, and Tb. The magnet basket matters because NdFeB demand is tied to electric mobility, wind power, robotics, industrial automation, and other high-efficiency applications. Dy and Tb are smaller-volume elements but can carry disproportionate value and supply risk. Project comparison should therefore report at least NdPr/TREO and DyTb/TREO when data permit, and should distinguish total magnet-REE content from the fraction actually recovered into saleable products (Heim & Vander Wal, 2023; International Energy Agency, 2026; Langkau & Erdmann, 2021).

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3.3. Emerging non-Chinese supply chains and Brazil's position

Brazil's most likely near-term role is as a diversified source of magnet-rich feed and intermediate products linked to non-Chinese separation and magnet supply chains while domestic capabilities develop. This hybrid approach is more credible than immediate full autarky. Experience from other supply-diversification efforts shows that bankability depends on offtake, product qualification, staged capacity, and policy tools that can absorb price volatility (Binnemans et al., 2021; Bogmans et al., 2026; Ilankoon et al., 2022). Brazilian projects benefit from mining expertise and renewable electricity, but these advantages do not eliminate the midstream learning curve or the need for long-term customer integration.

4. Geological Endowment and Deposit Diversity in Brazil

4.1. Ionic-adsorption and regolith-hosted deposits

The recent Brazilian investment cycle is strongly associated with deeply weathered regoliths in which REEs may be partly adsorbed on clay surfaces or associated with secondary Fe-Al phases. Such deposits are attractive because they can allow shallow mining and comparatively mild hydrometallurgical extraction, but the term "ionic clay" should not be used as a process guarantee. The desorbable fraction varies vertically and laterally; particle size, kaolinite and goethite associations, pH history, competing cations, and the proportion of structurally bound REE all affect recovery (Bishop et al., 2024; de Oliveira, 2026; Ding & Azimi, 2024; Russo et al., 2025; Santana & Botelho, 2022; Villanova-de-Benavent et al., 2026). Brazilian examples include Minaçu/Pela Ema, the Poços de Caldas region, Caldeira, Colossus, and Carina, but their mineralogy and metallurgy should be evaluated individually rather than treated as one deposit class.

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4.2. Carbonatite and alkaline-complex deposits

Brazil hosts world-class alkaline-carbonatite systems, including Araxá, Catalão, Tapira, and Poços de Caldas, which may contain monazite, bastnäsite, apatite, Nb minerals, and complex supergene assemblages. These systems offer high-grade and co-product opportunities but may require intensive beneficiation, cracking, and impurity control. Araxá is particularly important because of its linked REE-niobium economics; Catalão provides a relevant monazite/phosphate processing context; and weathering creates distinct ore domains with different processing responses (Antoniassi et al., 2020; Biondi & Braga, 2023; St George Mining Limited, 2026).

4.3. Granitic, peralkaline, placer, and secondary resources

Granitic and peralkaline occurrences, such as Pitinga and Serra Dourada-type systems, expand the mineralogical range to include refractory silicates, xenotime phases, and Nb-Ta-U-Th-REE associations. Monazite-rich heavy-mineral sands represent an important historical resource but require explicit Th/U management. Secondary resources—including phosphogypsum, process residues, tailings, and NdFeB magnets—may reduce pressure on primary resources, although grade, heterogeneity, collection, and logistics remain critical (Binnemans et al., 2013; München et al., 2021; Author, 2025; Author, 2026b). This diversity is strategically useful only when process selection follows mineral deportment rather than forcing a single flowsheet across fundamentally different feeds.

Figure 1 locates selected deposit and project clusters used in this review and makes Brazil's national-scale geological diversity visible. The figure is schematic rather than cadastral: it connects approximate geographic clusters with the deposit classes discussed above and should not be interpreted as a map of legal concession boundaries (Agência Nacional de Mineração, 2025; Cunha et al., 2025).

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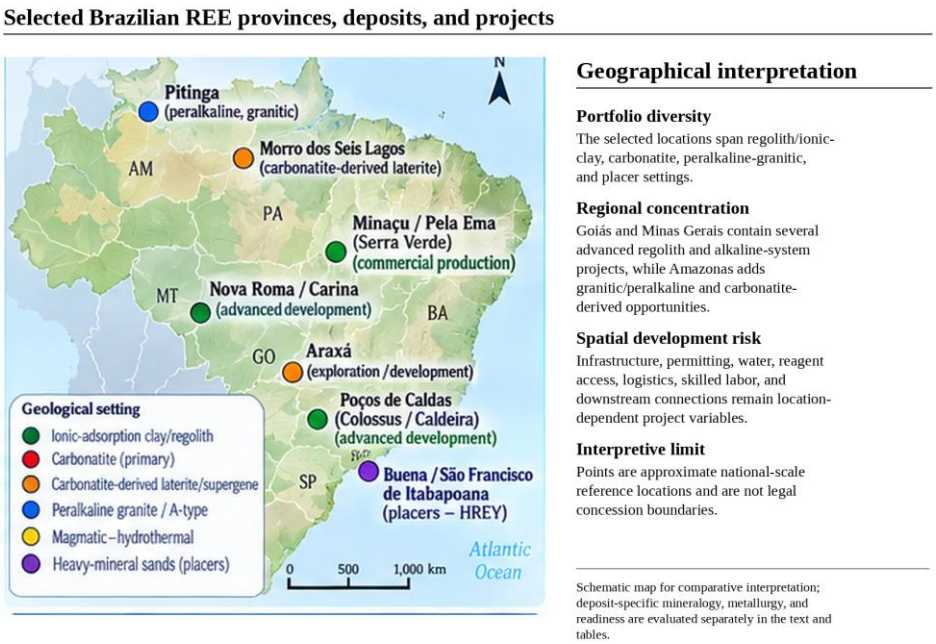

Figure 1. *Schematic geographical distribution of selected Brazilian REE deposits, resource clusters, advanced projects, and operating assets*

Note. Author synthesis adapted from Agência Nacional de Mineração (2025), Cunha et al. (2025), and public project disclosures reviewed in this article. Locations are approximate national-scale reference points and are not intended as legal concession boundaries.

Figure 1 reinforces two strategic observations. First, Brazil is not dependent on a single geological model: Goiás and Minas Gerais contain important regolith and alkaline systems, while Amazonas adds granitic/peralkaline and carbonatite-derived opportunities and coastal southeastern regions add placer potential. Second, infrastructure, permitting, water, reagent access, logistics, skilled labor, and proximity to downstream customers are spatial variables; comparable mineralogy can therefore carry different development risk at different locations.

Table 2 summarizes the mineralogical distinctions that should guide process selection. Table 2 explicitly links deposit type to REE deportment and to the process risk that most directly influences the R2V Gap (Alves et al., 2021; Antoniassi et al., 2020; Cheng et al., 2024; Demol et al., 2022).

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Table 2. *Major Brazilian REE deposit/feed types, mineralogical characteristics, and processing implications*

Deposit/feed	Representative setting and deportment	Preferred process logic	Primary risk
Ionic/regolith	Minaçu, Caldeira, Colossus, Carina; exchangeable REE with variable clay/Fe-Al association	Selective mining; screening/washing; salt desorption; impurity polishing	Desorbable fraction; Al-Ca-Mg-Fe co-extraction
Carbonatite/alkaline	Araxá, Catalão, Tapira; monazite/bastnäsite/apatite and Nb phases	Comminution/beneficiation; acid or alkaline cracking; leaching	Mineralogical complexity; P, Fe, Ca and radionuclides
Granitic/peralkaline	Pitinga and Serra Dourada-type systems; refractory silicates/xenotime, U-Th-Nb-Ta associations	Physical pre-concentration plus thermal/chemical activation	Refractoriness and radioactive-element deportment
Monazite sands	Coastal/paleoplacer monazite with ilmenite/zircon	Gravity/magnetic/electrostatic separation; chemical cracking	Th/U management and residue licensing
Secondary/recycling	Phosphogypsum, residues, tailings and NdFeB scrap	Collection/pre-concentration; selective leach or direct recycling	Low-grade variability or collection/qualification constraints

Note. Evidence synthesis adapted from Alves et al. (2021), Antoniassi et al. (2020), Cheng et al. (2024), Demol et al. (2022), and related Brazilian sources cited in this article.

The table also explains why the phrase “Brazilian REE ore” is analytically weak. Ionic-regolith material, monazite-bearing carbonatite, peralkaline silicates, and recycled magnets belong to different unit-operation families. Their recoverable value must be estimated with different liberation, reaction, purification, and residue models.

5. From Resources to Operations: The Brazilian REE Project Pipeline

5.1. Serra Verde–Pela Ema: the operating benchmark

Serra Verde is the key operating benchmark because it has crossed the boundary that most Brazilian REE projects have not: commercial production. The Pela Ema ionic-clay deposit entered commercial production in early 2024. The company aims to reach approximately 6,400 t REO per year by the end of 2027 and emphasizes a product basket containing Nd, Pr, Dy, and Tb (Serra

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Verde Group, 2024). Serra Verde's significance therefore exceeds annual tonnage. It demonstrates that Brazilian regolith can be mined, leached, concentrated, and sold at industrial scale, creating a reference for operating discipline, reagent management, product specification, logistics, offtake, and expansion. At the same time, MREC production remains an intermediate step and does not, by itself, close Brazil's separation and magnet-manufacturing gaps.

5.2. Caldeira: scale versus basket and process discipline

The Caldeira Project illustrates the opportunity and risk created by very large regolith resources. Public project reporting describes a resource on the order of 1.6 Bt at approximately 2,317 ppm TREO and a high magnet-REE contribution; feasibility work has evaluated a 6 Mt/y processing basis and average REO production in excess of 13 kt/y (Meteoric Resources NL, 2026). For such a large resource, another incremental increase in tonnes is less strategically important than evidence on spatial variability, desorbable recovery, solution impurity loads, water and reagent recycle, MREC quality and the robustness of the process under continuous operation. Scale can improve mine life and optionality, but it can also magnify weak assumptions in recovery or residue management.

5.3. Colossus: high-grade regolith and product-quality evidence

Colossus provides another large regolith case, with a reported global mineral resource of about 493 Mt at 2,508 ppm TREO and approximately 601 ppm magnet rare-earth oxide (MREO), equivalent to about 24% MREO/TREO. The project has advanced through feasibility-stage work and has emphasized high-purity MREC production (Viridis Mining and Minerals Limited, 2025). Its critical test is no longer simply whether high-grade zones exist, but whether variability across northern and southern domains can be translated into stable leach response, low impurity carry-over, repeatable product specification, realistic reagent consumption, and a bankable scale-up sequence. In R2V terms, the quality of evidence connecting resource blocks to product quality matters as much as the headline resource.

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5.4. Carina: feasibility, heavy-REE content, and integration strategy

Carina is a particularly useful comparator because its 2026 feasibility study reports both resource/reserve metrics and a defined product strategy. The project has reported measured-and-indicated resources of roughly 260.8 Mt at about 1,610 ppm TREO, a meaningful Dy-Tb contribution, average planned production of about 4,378 t/y TREO, and MREC purity near 97.7%, with start-up targeted for 2028 (Aclara Resources Inc., 2026). Its technical proposition combines low-strip regolith mining with water and reagent recycling, integrated into a broader separation strategy. Carina therefore illustrates how a smaller resource than Caldeira can still be strategically compelling when magnet-REE distribution, recoverability, product quality, and commercial integration are strong.

5.5. Araxá REE–Nb: co-product economics and mineralogical intensity

Araxá represents a different strategic model. The 2026 updated resource estimate reports 3.98 Mt of contained TREO, including approximately 0.76 Mt of NdPr oxides, together with about 0.63 Mt Nb_2O_5 (St George Mining Limited, 2026). Such co-location makes single-commodity evaluation inadequate: niobium credits may support infrastructure and project economics, while REE recovery may create an additional value stream. However, carbonatite mineralogy can require more intensive beneficiation and chemical cracking than regolith desorption. The project therefore tests whether very high contained value can offset greater flowsheet complexity, impurity-management requirements, and capital intensity. It also illustrates that “high grade” and “simple metallurgy” are distinct attributes.

5.6. Earlier, emerging, and secondary opportunities

Pitinga, Catalão, Tapira, Serra Dourada-type regoliths, phosphogypsum and mine residues preserve a broad option set beyond the five most visible projects. Pitinga shows the coexistence of REE with Nb-Ta-U-Th mineralization; Catalão provides an important monazite/phosphate

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processing context; phosphogypsum and tailings offer circular-economy potential; and Brazilian NdFeB recycling research bridges to urban secondary resources (München et al., 2021; Santana & Botelho, 2022). These opportunities should be screened with the same R2V logic as primary mines: recoverable basket, impurity burden, product route, residue closure, and market access.

Table 3 compares the principal project archetypes used in the review. Table 3 intentionally avoids a single "best project" ranking because each reported metric is conditioned by deposit type, reporting code, cut-off, extraction basis, and project stage (Aclara Resources Inc., 2026; Meteoric Resources NL, 2026; Serra Verde Group, 2024; St George Mining Limited, 2026; Viridis Mining and Minerals Limited, 2025).

Table 3. *Selected Brazilian REE projects: scale, basket indicators, stage, product route, and principal R2V bottleneck*

Project	Resource and magnet-REE signal	Stage / product (Sep. 2026)	Principal R2V bottleneck
Serra Verde / Pela Ema	Operating ionic-clay asset; Nd-Pr-Dy-Tb-rich basket	TRL-REE 5; commercial MREC / REO-equivalent concentrate	Ramp-up, product optimization and downstream separation
Caldeira	~1.6 Bt @ ~2,317 ppm TREO; ~22% MREO/TREO	TRL-REE 4; feasibility/pilot MREC route	Continuous-scale selectivity, permitting and financing
Colossus	493 Mt @ 2,508 ppm TREO; 601 ppm MREO (~24%)	TRL-REE 4; feasibility-stage high-purity MREC	Variability control, financing and execution
Carina	Measured + indicated ~260.8 Mt @ ~1,610 ppm TREO; ~22% magnet REO ratio	TRL-REE 4; ~97.7% MREC and integrated separation strategy	Permitting/execution and product-market integration
Araxá REE–Nb	3.98 Mt contained TREO incl. 0.76 Mt NdPr; 0.63 Mt Nb_2O_5	TRL-REE 2–3; REE + Nb co-product route under development	Beneficiation/cracking complexity and integrated metallurgy
Emerging/secondary set	Heterogeneous primary and secondary resources	TRL-REE 1–3; project-specific products	Resource definition, selective recovery and economics

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Note. Project-status evidence summary synthesized from Aclara Resources Inc. (2026), Meteoric Resources NL (2026), Serra Verde Group (2024), St George Mining Limited (2026), and Viridis Mining and Minerals Limited (2025). Metrics are not strictly comparable across reporting codes and process bases; they illuminate decision variables rather than valuation.

The key takeaway from Table 3 is that project maturity is multidimensional. Serra Verde leads on operating evidence; Carina, Caldeira, and Colossus provide increasingly detailed feasibility and pilot evidence; and Araxá has exceptional contained inventory but a different process-intensity profile. A ranking based on resource tonnage alone would obscure these distinctions.

6. Mineralogy, Deportment, and Beneficiation: Why Brazilian REE Resources Are Not Equivalent

6.1. REE host phases and exchangeability

Mineralogy is the first processing constraint after resource definition because it determines whether REEs are exchangeable at mineral surfaces, hosted in discrete REE minerals, incorporated into gangue lattices, or associated with Fe-Al oxides and phosphates. In regolith, adsorption and desorption depend on clay surface chemistry and competing ions; in carbonatites, monazite, bastnäsite, apatite and secondary phases define liberation and cracking behavior; in peralkaline systems, refractory silicates can dominate the process penalty (Antoniassi et al., 2020; Bishop et al., 2024; Ding & Azimi, 2024; He et al., 2023; Villanova-de-Benavent et al., 2026; Wu et al., 2023). Two ores with identical TREO can therefore require radically different energy, reagent, and purification intensity.

6.2. Weathering profile, vertical variability, and mineral liberation

Weathering can enrich, redistribute, and immobilize REEs simultaneously. Brazilian studies of deeply weathered alkaline and granitic systems reveal vertical profiles with distinct mineralogical zones, different REE host phases, and varying proportions of labile and refractory material (de Oliveira, 2026; Santana & Botelho, 2022). For regolith projects, selective mining by

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horizon can be as important as downstream leaching. In hard-rock or saprolitic ores, comminution and liberation should be justified by incremental recovery because excessive grinding increases energy consumption, ultrafine generation, and downstream separation challenges.

6.3. Beneficiation as value protection, not only mass rejection

Evaluate beneficiation by how effectively it protects downstream selectivity, not only by mass rejection or concentrate grade. Physical separation can reject gangue, concentrate discrete REE minerals, segregate radioactive or phosphate-rich fractions, and stabilize feed variability. Poorly designed pre-concentration, however, can lose ultrafine REE-bearing phases or generate slimes that hinder flotation, filtration, and leaching. Recent studies emphasize the importance of particle size, mineral associations, and reagent selectivity (Cheng et al., 2024; Jordens et al., 2013). Within the R2V framework, beneficiation creates value when it reduces reagent consumption and impurity burden per unit of recovered magnet REO while preserving overall product recovery.

Figure 2 presents the deposit type–mineralogy–processing-route relationships that organize this section. Figure 2 emphasizes that Brazil's strategic advantage derives from portfolio diversity only if each feed is matched to an appropriate liberation, activation, leaching, and purification sequence (Alves et al., 2021; Cheng et al., 2024; Demol et al., 2022).

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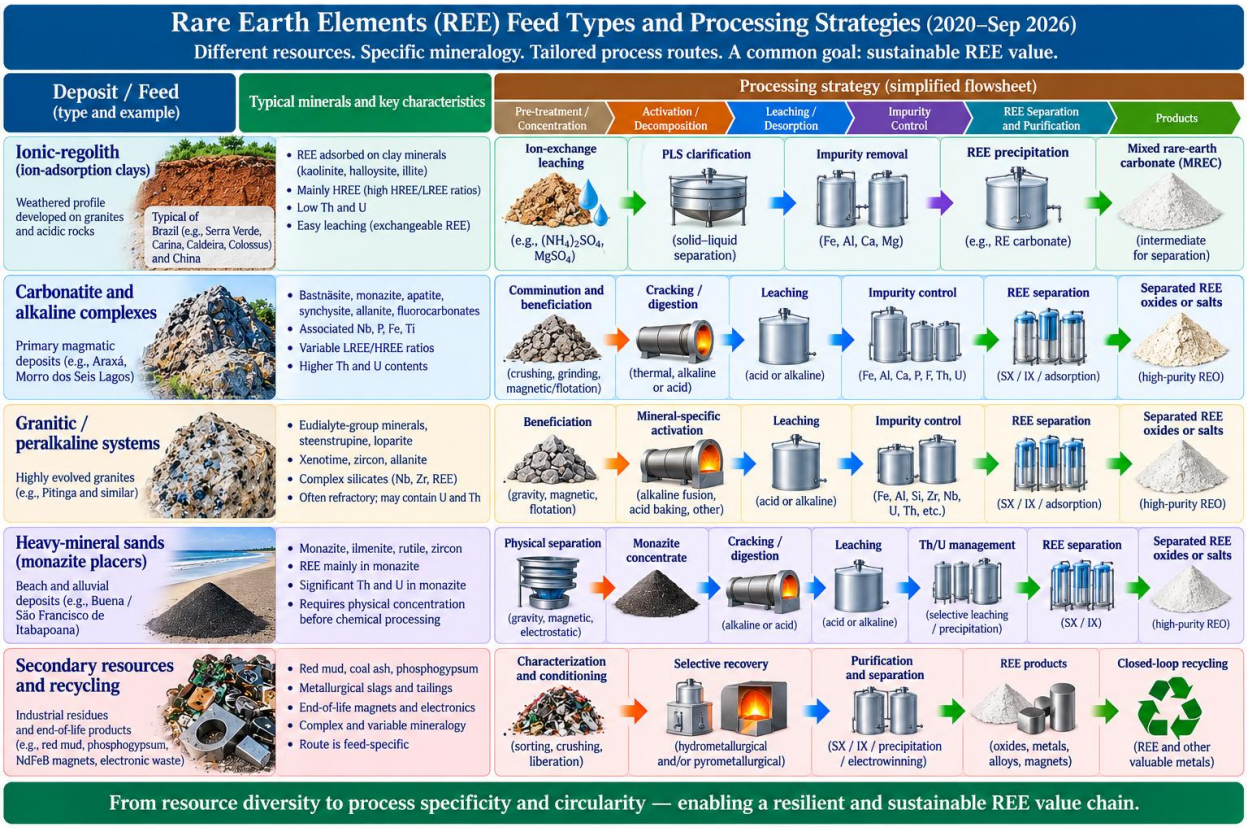

Figure 2. *Deposit type–mineralogy–processing-route relationships for Brazilian REE resources*
Note. Author synthesis adapted from Alves et al. (2021), Antoniassi et al. (2020), Cheng et al. (2024), Demol et al. (2022), and related sources cited in this article.

Figure 2 also makes clear why flowsheet transfer between projects should be resisted. Mild salt desorption is appropriate only where a meaningful fraction of the REE inventory is exchangeable; monazite and refractory silicates require chemical activation; and secondary feeds frequently need a front-end collection or pre-concentration step before hydrometallurgy becomes economically meaningful.

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7. Extraction Metallurgy and the Selectivity Bottleneck

7.1. Ionic-clay and regolith leaching

Salt leaching of ion-adsorption ores is governed primarily by ion exchange rather than indiscriminate mineral dissolution. Ammonium salts are effective but create a recognized nitrogen-discharge risk; magnesium sulfate and related divalent salts have therefore attracted attention as potentially lower-impact alternatives when ionic strength, impurity mobilization, and recycle chemistry are properly controlled (Ahmed et al., 2025; Azimi, 2025; Li et al., 2024; Author, 2026a; Wang et al., 2025; Yudha et al., 2026). The central design variables are reagent identity and concentration, pH, liquid-to-solid ratio, contact time, permeability, feed mineralogy, and recycle chemistry. The preferred operating window is therefore not necessarily the condition of maximum REE extraction, but the condition that maximizes saleable REE recovery while minimizing impurity co-extraction, reagent consumption, and downstream purification duty.

7.2. Calcium, magnesium, aluminum, and iron as process penalties

The selectivity bottleneck is evident in the behavior of common gangue cations. Ca and Mg can consume precipitation reagents, alter solvent-extraction loading, and generate scaling; Al can be strongly mobilized from clay systems and compete in purification; Fe can hydrolyze, precipitate, or entrain REE depending on redox and pH. Mechanistic studies show that leachant composition and Al content can strongly change the apparent efficiency of Mg-sulfate systems (He et al., 2023; Judge & Azimi, 2020; Liu et al., 2025). A flowsheet that reports 90% REE extraction but transfers a large impurity mass into the pregnant solution may be inferior to a lower-extraction route that reduces neutralization, filtration, and separation duty.

7.3. Hard-rock, carbonatite, and monazite resources

Hard-rock and carbonatite resources require a different reaction logic. Acid baking, roasting, caustic digestion, and direct acid leaching break refractory REE minerals, but each route

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redistributes sulfate, phosphate, silica, iron, and radionuclides differently. Studies of monazite and mixed concentrates demonstrate that gangue minerals can either hinder or unexpectedly assist cracking and leaching, reinforcing the need for feed-specific reaction models (Alves et al., 2021; Demol et al., 2022). Brazilian carbonatite opportunities should therefore be developed through integrated beneficiation–cracking–leaching test programs rather than by optimizing each unit operation in isolation.

7.4. Radioactive elements and residues

Monazite- and Pitinga-type systems make Th/U control a design variable rather than a downstream compliance afterthought. Selective isolation of Th, U, and Ra can require dedicated solvent extraction, precipitation, or residue-routing steps, while inappropriate pH control can redistribute radionuclides into larger waste volumes (Hamza et al., 2026; Su et al., 2021). The preferred process boundary concentrates radionuclides into a stable, licensable residue while maximizing REE recovery and minimizing secondary liquid waste. This criterion is central to social license and bankability for hard-rock projects in Brazil.

Table 4 compares the major beneficiation and extraction route families relevant to Brazilian deposits. Table 4 frames the trade-off between extraction intensity and selectivity rather than maximum laboratory recovery (Ahmed et al., 2025; Azimi, 2025; Cheng et al., 2024; Demol et al., 2022; Li et al., 2024).

Table 4. *Comparison of beneficiation and extraction route families relevant to Brazilian REE resources*

Feed archetype	Front-end and extraction route	Main advantage	Main selectivity / scale-up risk
Ionic/regolith clay	Selective mining/screening -> $MgSO_4$ or other salt desorption	Low-intensity extraction; limited comminution	Al-Ca-Mg-Fe co-desorption; permeability; recycle accumulation
Ionic/regolith clay	Selective mining/screening -> ammonium-salt exchange	High exchange efficiency; established chemistry	Ammonium discharge and water-treatment burden

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Carbonatite / monazite-rich	Comminution/beneficiation -> acid bake/roast -> leach	High conversion of refractory REE minerals	Acid use; sulfate/phosphate burden; Th/U routing
Refractory granitic/peralkaline	Fine grinding/pre-concentration -> acid/alkaline activation	Access to structurally bound REE	Energy, silica gelation and refractory residues
Secondary residues / NdFeB	Sorting/pre-concentration -> selective leach or direct recycling	Circular feed and potentially high REE concentration	Matrix variability, collection economics and product qualification

Note. Adapted from Ahmed et al. (2025), Azimi (2025), Cheng et al. (2024), Demol et al. (2022), Li et al. (2024), Pereira (2026a), and Wang et al. (2025).

Table 4 shows that the apparent environmental advantage of mild leaching can disappear if low extraction forces excessive ore movement or if recycle streams accumulate impurities. Likewise, an energy-intensive cracking route can be defensible when it generates a high-recovery, high-purity product from a rich feed with well-managed residues. Process comparisons must therefore use a consistent functional unit, preferably per kilogram of saleable magnet REO.

Table 5 focuses on impurities because they are the hidden bridge between leaching and product quality. Table 5 identifies where each impurity enters the flowsheet and which downstream penalty to measure (Judge & Azimi, 2020; Su et al., 2021).

Table 5. *Impurity behavior and selectivity limitations across Brazilian REE flowsheets*

Impurity	Source/behavior	Downstream penalty	Preferred control logic
Al	Clay/aluminosilicate dissolution and hydrolysis	Reagent use, precipitation bulk, SX interference	Selective leach window; staged pH removal; recycle monitoring
Fe	Fe-oxide dissolution or colloidal carry-over	Entrapment, contamination, filtration burden	Redox/pH control; pre-removal and clarification
Ca + Mg	Carbonates/apatite/exchangeable cations; high soluble load	SX competition, scaling and reagent demand	Selective leach; purge/bleed; precipitation management
P	Apatite/monazite/phosphate residues	REE precipitation losses and residue volume	Mineralogical rejection; controlled cracking/precipitation
Th + U (+Ra)	Radioactive accessory phases; route-dependent dissolution	Licensing, radiation protection, waste classification	Dedicated partitioning and stable residue confinement
Si/colloids	Silicate dissolution, polymerization and ultrafines	Poor filtration, entrainment and scaling	Avoid over-dissolution; solids control; liquor conditioning
NH4-N	Ammonium-based ion-exchange leaching	Eutrophication/toxicity and water-treatment duty	Leachant substitution/recovery; membrane/electrochemical treatment

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Note. Evidence synthesis adapted from Judge and Azimi (2020) and Su et al. (2021).

Impurity control is therefore a value-creation operation rather than merely a purification cost. Every kilogram of gangue removed before SX, precipitation, or crystallization reduces downstream equipment size and chemical demand. Selectivity should be reported as a flowsheet metric: recovered REE product divided by the impurity, reagent, water, and residue burden required to achieve specification.

8. Separation, Refining, and the Brazilian Midstream Gap

8.1. Mixed rare-earth carbonate is an intermediate, not an end-state

Mixed rare-earth carbonate (MREC) or mixed rare-earth oxide can be a commercially valuable product and an appropriate ramp-up target, but neither should be mistaken for the end-state of an integrated REE industry. The highest-value magnet chain generally requires purification, element-group separation, Nd/Pr and heavy-REE control, oxide finishing, metal/alloy conversion, and magnet qualification. Each additional step introduces its own impurity specifications, recycle streams, and yield losses. This is where the R2V Gap becomes most visible in Brazil: upstream mining and leaching capability is advancing faster than domestic individual-REE separation and large-scale magnet manufacturing (Centro Brasileiro de Relações Internacionais, 2026; Centro de Tecnologia Mineral, 2025a; Centro de Tecnologia Mineral, 2025b; Huang & Xie, 2025).

8.2. Solvent extraction, ion exchange, membranes, and emerging separations

Solvent extraction (SX) remains the reference technology for high-throughput rare-earth separation because multistage counter-current circuits can amplify small distribution-factor differences. Its scale-up disadvantages are also well established: large stage counts, substantial organic inventory, phase-disengagement requirements, crud formation, acid/base consumption, and sensitivity to impurity loading. Ion exchange (IX) and extraction chromatography can provide

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high selectivity for polishing or smaller streams, whereas membranes, electrochemical systems, and other emerging technologies offer opportunities for process intensification but still require demonstration against industrial throughput, lifetime, selectivity, and purity targets (Dewulf et al., 2022; El Ouardi et al., 2023; Guo et al., 2026; Xie et al., 2014).

8.3. Nd/Pr and Dy/Tb as distinct separation problems

Nd/Pr and Dy/Tb should be treated as different technical and market problems rather than as one generic "rare-earth separation" task. Nd and Pr are adjacent light lanthanides with similar chemistry, and many magnet supply chains can accept a combined NdPr oxide; the practical objective is therefore often robust group separation, impurity control, and consistent NdPr specification rather than complete Nd-versus-Pr fractionation. Dy and Tb, by contrast, normally occur at much smaller mass flow but carry disproportionate strategic and economic importance in high-coercivity magnet applications. Their recovery is therefore highly sensitive to small absolute yield losses, entrainment, bleed streams, and polishing efficiency, and can justify dedicated heavy-REE scrubbing, stripping, ion-exchange, or other polishing stages. Feed composition, customer specification, stage count, recovery, purity, product premium, and recycle losses should consequently be reported separately for NdPr and Dy/Tb rather than collapsed into a single separation-readiness statement (Dewulf et al., 2022; Guo et al., 2026; Gutfleisch et al., 2011; Heim & Vander Wal, 2023).

8.4. Brazilian capability building

Brazil has begun to address the midstream gap through technology programs rather than relying only on mine development. MagBras was launched to demonstrate a complete domestic permanent-magnet cycle from mineral processing through separation/refining, magnet fabrication, application, and recycling; CETEM's role includes extraction, solvent extraction, and refining of Pr, Nd, Tb, and Dy. Regina II similarly targets REE separation, metal reduction/refining, alloy metallurgy, and magnet manufacture (Centro de Tecnologia Mineral, 2025a; Centro de Tecnologia

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Mineral, 2025b). These initiatives are strategically important because they connect pilot science with the qualification and manufacturing steps that determine whether upstream value remains in Brazil.

Figure 3 depicts the Resource-to-Value chain and identifies the Brazilian midstream gap. Figure 3 places the major bottleneck after MREC because value capture increasingly depends on separated oxide specification, alloy/magnet conversion, and customer qualification (Centro Brasileiro de Relações Internacionais, 2026; Centro de Tecnologia Mineral, 2025a; Huang & Xie, 2025; Serra Verde Group, 2024).

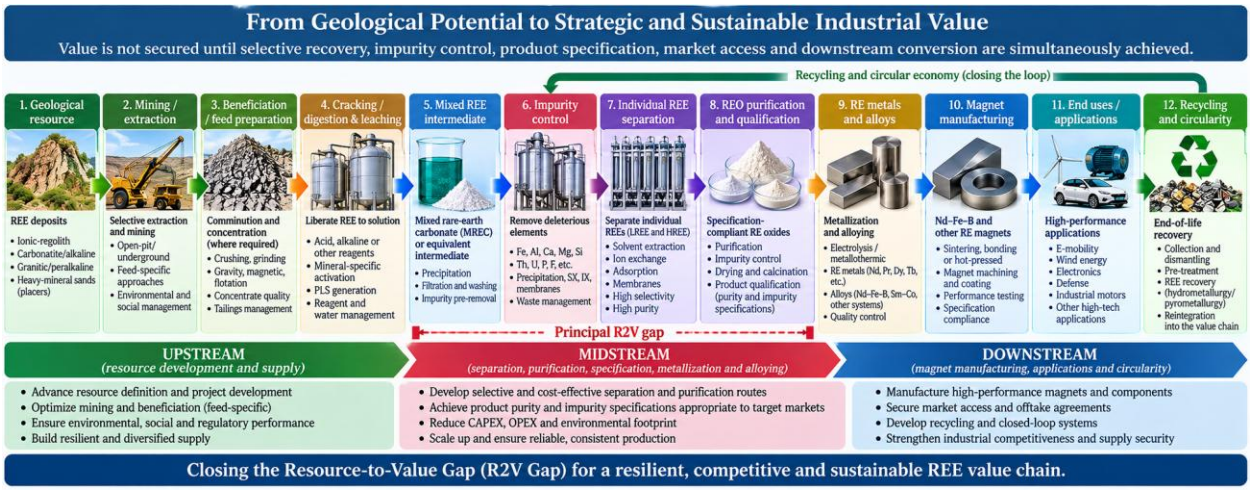

Figure 3. *Brazilian REE resource-to-value chain and the upstream–midstream–downstream maturity gap*
Note. Author synthesis adapted from the project pipeline, Centro Brasileiro de Relações Internacionais (2026), Centro de Tecnologia Mineral (2025a, 2025b), Huang and Xie (2025), and Serra Verde Group (2024).

The placement of the bottleneck in Figure 3 should not be interpreted as a claim that upstream metallurgy is solved. Rather, it means that successful mines now make the absence of integrated midstream capacity more consequential. As MREC output grows, domestic or allied separation capacity must grow with it, or the country will continue exporting a substantial part of the chemical and manufacturing value embedded in its resources.

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Table 6 summarizes Brazilian midstream and downstream initiatives. Table 6 distinguishes current commercial activity from demonstration and R&D so that policy ambition is not confused with installed industrial capacity (Centro Brasileiro de Relações Internacionais, 2026; Centro de Tecnologia Mineral, 2025a; Centro de Tecnologia Mineral, 2025b; München et al., 2021; Author, 2026b; Serra Verde Group, 2024).

Table 6. *Brazilian midstream/downstream initiatives: separation, refining, recycling, alloys, and magnets*

Initiative	Technology boundary	Readiness signal	Strategic significance
Serra Verde / Pela Ema	Mine + leach + mixed REE product	Commercial operation	Anchors Brazilian magnet-REE feed but does not complete domestic separation
MagBras	Mine -> separation/refining -> magnet -> application/recycling	National demonstration program	Targets full-cycle domestic capability and magnet qualification
Regina II	Separation, metal reduction/refining, alloys and magnets	R&D / pilot	Builds high-value conversion know-how
Project-linked MREC pilots	Integrated leach, impurity removal and MREC production	Pilot/feasibility	Reduces scale-up risk before mine construction
Brazilian NdFeB recycling research	Collection/demagnetization, direct or hydromet recycling	Lab to pilot	Creates future domestic secondary feed and circularity option
University/CETEM separation research	SX, IX, precipitation and selective recovery	R&D / pilot	Supports impurity control and individual-REE separation

Note. Adapted from Centro Brasileiro de Relações Internacionais (2026), Centro de Tecnologia Mineral (2025a, 2025b), München et al. (2021), Pereira (2026b), and Serra Verde Group (2024).

The strategic lesson from Table 6 is that Brazil already has many of the knowledge components required for a mine-to-magnet chain, but they are unevenly connected and not yet all represented at commercial scale. The policy problem is therefore one of integration, sustained pilot infrastructure, customer qualification and capital—not merely one of laboratory invention.

9. Environmental Performance, Radioactivity, Water, and Social License

9.1. Deposit type does not determine impact by itself

Simple labels such as “ionic clay = low impact” or “hard rock = high impact” are inadequate. Ionic-regolith mining may avoid intensive comminution and wet tailings, but environmental performance still depends on land disturbance, water balance, salt use, ammonium or sulfate

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release, impurity mobilization and rehabilitation. Hard-rock projects consume more comminution and cracking energy but can sometimes concentrate residues in smaller engineered streams and benefit from established mine infrastructure. Comparative environmental assessment should therefore normalize impacts to saleable REE product and include recovery and product purity (Langkau & Erdmann, 2021; Schreiber et al., 2021; Wang et al., 2025).

9.2. Water, reagent recovery, and closed-loop operation

Water is both an environmental and metallurgical variable. Regolith leaching requires careful control of solution distribution, drainage and recycle chemistry; repeated recycle can reduce freshwater demand but may accumulate Ca, Mg, Al, sulfate, chloride or ammonium species that eventually reduce extraction selectivity or increase scaling. Treatment technologies for ammonium-rich REE mine waters show that nitrogen management can become a dedicated unit operation (Guedes et al., 2026; Wang et al., 2025). The appropriate performance indicators are therefore freshwater make-up, recycle fraction, purge composition, reagent make-up per kilogram REO, and contaminant mass leaving the closed loop.

9.3. Tailings, backfilling, and rehabilitation

Select the residue strategy together with mineralogy. Low-intensity regolith operations may generate washed or leached solids that can potentially be returned to mined areas when geotechnical and geochemical conditions permit. Hard-rock flowsheets create beneficiation tailings and chemical residues that may require separate management. Tailings valorization and secondary REE recovery can reduce long-term liabilities, but only if additional processing does not shift impacts to reagent consumption or contaminated effluents. Rehabilitation performance should therefore be measured by physical stability, water quality, and restoration outcomes rather than by the absence of a conventional tailings dam alone.

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9.4. Thorium, uranium, and radiological stewardship

Radioactive-element management is especially material for monazite and U-Th-rich granitic systems. Environmental and occupational risk depends on mineralogy, dust control, process partitioning, residue activity, storage design, and long-term monitoring. Global evidence from REE-producing regions illustrates how radiological contamination can become a social-license issue when residues and soils are not tightly controlled (Hamza et al., 2026; Su et al., 2021). For Brazil, the technically strongest path is early characterization of Th/U/Ra deportment, explicit separation targets, and a residue specification that can be licensed before commercial scale is committed.

9.5. Life-cycle assessment and functional-unit discipline

Life-cycle assessment (LCA) conclusions are highly sensitive to functional unit and system boundary. Per-tonne-of-ore comparisons can favor low-grade, high-throughput systems or obscure the benefits of higher recovery. A per-kilogram-TREO basis can also mislead when the product mix is dominated by lower-value La/Ce. For magnet-oriented projects, a more decision-relevant basis is the mass of specification-compliant NdPr plus Dy/Tb, with transparent co-product allocation. Recycled feed can reduce impacts, but collection, preprocessing, recovery, and separation remain important contributors (Langkau & Erdmann, 2021; Schreiber et al., 2021).

Table 7 integrates the main ESG and regulatory issues. Table 7 links each issue to an auditable metric so that sustainability claims can be tested against operating data (Guedes et al., 2026; Hamza et al., 2026; Langkau & Erdmann, 2021; Schreiber et al., 2021; Wang et al., 2025).

Table 7. *ESG, radioactive-element, water, tailings, and regulatory issues for Brazilian REE development*

Issue	Preferred KPI	Main risk	Design response
Water balance	m³ freshwater/kg saleable REO; recycle %	Water demand and recycle-salt accumulation	Closed loop, stormwater segregation, controlled purge
Reagent burden	kg reagent/kg saleable REO; recovery %	OPEX and effluent load	Reagent recovery and selective operating window
Ammonium / N	kg N discharged/kg REO; NH4-N	Water-quality and treatment burden	Alternative salts, recovery and dedicated treatment

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Tailings/residue	kg residue/kg saleable REO; leachability	Land footprint and long-term liability	Dry management/return where suitable; monitoring
Th/U/Ra	Activity balance in product, residue and water	Licensing and occupational/radiological risk	Early deportment, selective partitioning, stable confinement
Carbon footprint	kg CO_2-e/kg saleable magnet REO	Product qualification and climate claims	Renewable power, lower comminution, reagent optimization
Social license	Rehabilitation, water compliance, grievance closure	Permitting continuity and local legitimacy	Early engagement, transparent monitoring, progressive rehabilitation

Note. Adapted from Guedes et al. (2026), Hamza et al. (2026), Langkau and Erdmann (2021), Schreiber et al. (2021), and Wang et al. (2025).

This framework makes ESG a design input rather than a post-project disclosure. The preferred flowsheet sustains recovery and product quality while maintaining water, residue, and radiation controls over the entire mine life—including less favorable ore domains often underrepresented in early test programs.

10. Economics, Infrastructure, and Project Bankability

10.1. Grade versus recoverable value

REE economics are highly sensitive to product mix and recovery. A project may have high TREO grade but low value if most TREO is La-Ce or if magnet REEs are refractory; alternatively, a moderate-grade regolith can be attractive if Nd-Pr-Dy-Tb are abundant, easily desorbed, and upgraded into a clean product. Economic assessments of unconventional REE feedstocks and project costs show that grade must be linked to recoverability, scale, process intensity, and product price rather than interpreted alone (Collerson et al., 2025; Fritz et al., 2023; O'Brien & Alonso, 2025).

10.2. Recoverable Basket Value

To make the link between grade, recovery, and product value explicit, this review proposes Recoverable Basket Value (RBV) as a screening metric for comparing ore domains or projects on a common product basis. Using one tonne of feed as the reference basis, RBV can be written as:

$$RBV = \Sigma_i (C_i \times R_i \times P_i),$$

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where C_i is the contained mass of REE i per tonne of feed (kg REE_i/t feed), R_i is the overall dimensionless recovery of REE i to the specified saleable product, and P_i is the corresponding conservative product netback (US$/kg REE_i in that product). On this basis, RBV is expressed in US$/t feed. If you need project-wide inventory value, apply the feed-tonnage basis separately rather than embedding it in C_i. Always report RBV with the assumed product form, payable terms, separation costs, and price date. Its purpose is not to create a universal "value per tonne" ranking, but to show how much geological basket value survives mineral processing, separation, and product qualification. For magnet-focused projects, Nd, Pr, Dy, and Tb often dominate this calculation (Heim & Vander Wal, 2023).

Worked hypothetical example. Consider one tonne of feed containing 0.30 kg Nd, 0.08 kg Pr, 0.020 kg Dy, and 0.004 kg Tb. Assume overall recoveries to a defined saleable product of 70%, 68%, 60%, and 55%, respectively, and purely illustrative netbacks of US$60, US$65, US$250, and US$700 per kilogram. The screening value is RBV = (0.30 x 0.70 x 60) + (0.08 x 0.68 x 65) + (0.020 x 0.60 x 250) + (0.004 x 0.55 x 700) = US$20.68/t feed. These round numbers are intentionally hypothetical and are not market quotations. In any real application, the analyst must disclose the price date, product form, payability, separation and refining deductions, recovery basis, and reference unit. RBV is therefore a sensitivity-screening metric, not a feasibility-study valuation, net-present-value calculation, or investment metric.

10.3. Co-product credits and the Araxá case

Co-products can materially change a project's cost allocation and financing logic. Araxá is the clearest Brazilian example because its REE inventory is accompanied by a major niobium resource (St George Mining Limited, 2026). However, co-product credits should be conservative: they are valuable only if recovery circuits are technically compatible, product markets can absorb the volumes, and one commodity does not impose unacceptable penalties on the other. Similar logic

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applies to phosphate or tin-related secondary resources. A by-product is not "free"; it inherits collection, separation, and qualification costs.

10.4. CAPEX, OPEX, infrastructure, and scale-up uncertainty

Capital expenditure (CAPEX) and operating expenditure (OPEX) estimates for REE projects remain uncertain because separation circuits, reagent plants, water treatment, residue facilities, and product finishing can be significant even when mining itself is comparatively simple. Large-stage-count SX circuits are particularly sensitive to throughput, impurity loading, and recycle behavior. Brazilian infrastructure can reduce risk through established roads, power, labor, and logistics, but site-specific factors such as reagent supply, water availability, and port distance remain material. Cost estimates should therefore be stress-tested against recovery, acid or salt consumption, product purity, ramp-up duration, and price assumptions rather than relying on single deterministic values (Fritz et al., 2023; O'Brien & Alonso, 2025).

10.5. Offtake, price floors, and bankability

Because rare-earth prices are volatile and customer qualification is demanding, bankability often requires more than a positive discounted cash flow model. Long-term offtake, price support, strategic customers, and staged development can reduce revenue uncertainty. Global supply-chain studies show why projects can remain stranded despite attractive geology when downstream buyers, financing, and policy are not synchronized (Bogmans et al., 2026; Ilankoon et al., 2022). Brazil's strongest projects increasingly combine technical feasibility with explicit marketing and partnership strategies, narrowing the R2V Gap even before domestic downstream manufacturing is complete.

Figure 4 visualizes why TREO grade and magnet-REE basket quality must be treated separately. Figure 4 compares three advanced Brazilian regolith projects on public resource-grade and magnet-REE-ratio metrics, while showing Araxá separately because its latest headline is

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reported as contained inventory rather than the same regolith-resource basis (Aclara Resources Inc., 2026; Meteoric Resources NL, 2026; St George Mining Limited, 2026; Viridis Mining and Minerals Limited, 2025).

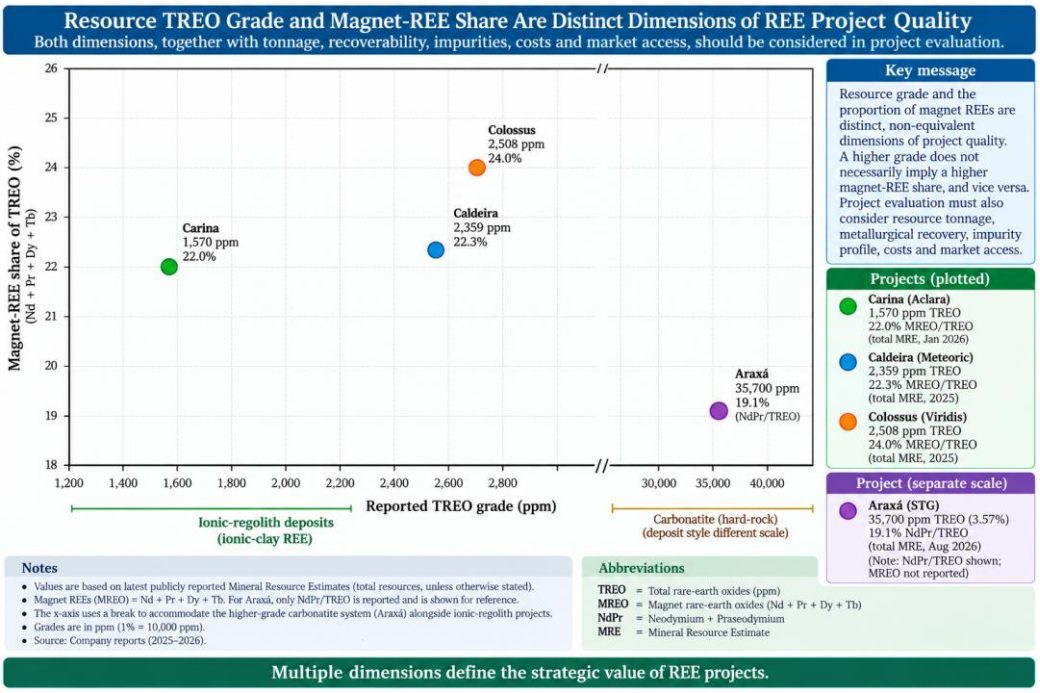

Figure 4. *REE basket quality: reported TREO grade versus magnet-REE contribution for selected Brazilian projects*

Note. Author synthesis from Aclara Resources Inc. (2026), Meteoric Resources NL (2026), St George Mining Limited (2026), and Viridis Mining and Minerals Limited (2025). Bubble sizes schematically indicate reported resource scale and are not valuation weights.

The narrow magnet-REE ratio range among the plotted regolith projects is informative: small grade differences do not dominate project value. Recovery, product specification, operating cost, permitting, financing, and the Dy/Tb contribution can outweigh a few hundred ppm of total grade. The appropriate economic comparison is therefore multi-variable and stage-aware.

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11. Market, Geopolitics, Industrial Policy, and Brazil's Strategic Options

11.1. China's mine-to-magnet dominance and diversification pressure

The international policy problem is not simply dependence on Chinese mine production; it is dependence on a deeply integrated ecosystem of separation, metals, alloys, magnets, equipment, reagents, technical knowledge, and customer networks. Trade-network and value-chain studies show that concentration persists even as new mines appear (Guo & Wang, 2024; Huang & Xie, 2025; International Energy Agency, 2026; Zuo et al., 2022). Brazil can contribute to diversification because it offers both LREE and HREE-bearing resources, but the strategic premium will be larger if Brazilian products progress beyond mixed concentrates toward separated magnet REEs and qualified downstream materials.

11.2. Resource supplier versus industrial participant

Brazil does not need to choose between being a resource exporter and a fully autarkic magnet producer. A staged model is more robust: scale competitive mines and MREC; develop domestic separation and refining for selected high-value products; integrate with allied offtake where this accelerates bankability; build metals, alloys and magnet capacity where customer demand and manufacturing competence justify it; and use recycling to supply a growing secondary loop. This strategy protects optionality while avoiding the risk of constructing downstream capacity without secure feed or customers (Centro Brasileiro de Relações Internacionais, 2026; Centro de Tecnologia Mineral, 2025a; Centro de Tecnologia Mineral, 2025b; Mindreau, 2025).

11.3. National strategy and regulatory evolution

Policy evolved rapidly during 2026. The Ministry of Mines and Energy began technical work on a National Rare Earth Strategy in January 2026, explicitly linking mining to industrial, environmental, innovation, and energy-transition policy (Ministério de Minas e Energia, 2026a). The subsequent strategy-support report identified Brazil's upstream concentration and the need for

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stronger separation/refining capability, financing, licensing, infrastructure, technology, and governance (Centro Brasileiro de Relações Internacionais, 2026). The broader Plano Nacional de Mineração 2050 provides a long-horizon mineral-policy context (Ministério de Minas e Energia, 2026b). Together, these initiatives recast REEs as an industrial value-chain challenge rather than a geological-inventory issue alone.

11.4. Critical-minerals legislation as of 9 September 2026

The legislative position must be dated carefully. As of 9 September 2026, PL 2780/2024—which establishes a National Policy for Critical and Strategic Minerals and a National Council for their industrialization—had been approved by the Senate and remitted for presidential sanction on 4 September; the sanction/veto window remained open. It should therefore not be described in this review as an already enacted law (Senado Federal, 2026). This distinction illustrates a broader methodological rule: tie fast-moving policy claims to a specific cut-off date, especially in a review intended to define the 2020–2026 landscape.

11.5. Strategic autonomy versus global integration

Strategic autonomy should be interpreted as the capacity to make choices, not as complete national self-sufficiency. Brazil gains bargaining power if it can produce multiple qualified product forms, route material to more than one separation/refining partner, and retain domestic capability in critical know-how. International partnerships can accelerate learning, financing, and qualification, while domestic pilot and manufacturing programs prevent permanent dependence on external midstream technology. The optimal balance is therefore "globally integrated but technologically capable," with policy incentives conditioned on measurable value addition and environmental performance.

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12. Critical Synthesis: From Geological Potential to a Brazilian Mine-to-Magnet Strategy

12.1. The Brazilian REE Value-Chain Readiness framework (BREE-VCR)

The Brazilian project pipeline requires a comparison framework that goes beyond resource size. This review therefore proposes the Brazilian REE Value-Chain Readiness framework (BREE-VCR), structured around nine dimensions: G, geological confidence; R, resource quality; M, metallurgical maturity; S, separation readiness; E, ESG performance; I, infrastructure; F, financing; O, offtake security; and D, downstream integration. Each dimension can be evaluated on a transparent ordinal scale only when supporting evidence is available, but BREE-VCR is intended primarily as a structured evidence checklist rather than a single composite score. High geological confidence cannot automatically compensate for weak metallurgy, permitting, financing, product qualification, or market connection. The framework complements, rather than replaces, TRL-REE: the R2V Gap defines where value can be lost, TRL-REE describes project evidence maturity, and BREE-VCR identifies which parts of the integrated value chain remain weak. Table 8 operationalizes the nine dimensions through evidence indicators and low- versus high-readiness signals.

Table 8 converts BREE-VCR from a conceptual list into an auditable matrix. Record evidence dimension by dimension rather than averaging it into a single investment-style score.

Table 8 BREE-VCR dimensions, evidence indicators, and readiness boundaries

Dimension	Definition	Evidence indicators / typical source	Low-readiness signal	High-readiness signal
G - Geological confidence	Confidence in continuity, geometry, grade, and classification.	Drilling density; resource category; reporting code; dated MRE/technical report.	Occurrence or poorly constrained inferred inventory.	Measured/indicated confidence with reconciled domains and traceable reporting basis.
R - Resource quality	Fraction of geological inventory plausibly	TREO plus NdPr/DyTb distribution;	Headline grade without	Resource quality linked spatially to

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	accessible to the selected route.	exchangeable/desorbable fraction; mineral deportment.	recoverability or basket definition.	recoverable magnet-REE basket.
M - Metallurgical maturity	Evidence that mining/beneficiation/leaching can deliver stable recovery and selectivity.	Variability testing; continuous pilot data; reagent intensity; impurity burden.	Isolated batch extraction results.	Integrated variability-tested flowsheet with mass balance and product-quality evidence.
S - Separation readiness	Capability to convert mixed products to separated, specification-compliant REE products.	SX/IX flowsheet; stage count; yield; purity; customer qualification.	MREC endpoint with no demonstrated separation route.	Qualified separated products with demonstrated recycle and impurity control.
E - ESG performance	Environmental, radiological, water, residue, and social-license evidence.	Water balance; reagent recycle; LCA; Th/U/Ra deportment; residue route; permits.	Generic sustainability claims or unresolved residue/water pathway.	Auditable saleable-product-normalized impacts and licensed closure strategy.
I - Infrastructure	Readiness of power, water, reagents, roads, ports, laboratories, and workforce.	Site studies; logistics; utility agreements; reagent supply.	Infrastructure assumed rather than demonstrated.	Site-specific access and capacity demonstrated for planned scale.
F - Financing	Ability to fund construction, ramp-up, working capital, and contingencies.	Financing plan; committed capital; sensitivity; staged development.	Conceptual CAPEX without credible funding path.	Financing structure aligned with study maturity and downside sensitivities.
O - Offtake security	Degree of customer linkage, payability clarity, and product-market qualification.	Offtake agreements/MOUs; specifications; payability; customer tests.	No defined buyer or product boundary.	Diversified qualified customers with transparent product/payability terms.
D - Downstream integration	Capability beyond mixed products into oxide finishing, metals, alloys, magnets, or recycling.	Domestic/allied separation; metal/alloy route; magnet pilot; recycling loop.	Export of unqualified mixed product as sole route.	Multiple qualified conversion pathways and retained technical know-how.

Note. Author-developed evidence matrix. Typical evidence sources include peer-reviewed process studies, reporting-code technical documents, dated government statistics, project technical disclosures, permitting records, customer

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qualification evidence, and financing/offtake documentation. BREE-VCR is a screening framework, not an investment rating.

12.2. Project-readiness map

Figure 5 places the principal projects on two separate author-defined 1–5 axes: overall project maturity, informed by the TRL-REE logic and public development evidence, and metallurgical/downstream readiness. The figure is deliberately heuristic and summarizes evidence density and stage rather than assigning a financial valuation. Serra Verde occupies the operating and high-readiness corner; Carina, Caldeira, and Colossus cluster in advanced pre-production space; and Araxá remains earlier in integrated flowsheet maturity despite its exceptional contained inventory (Aclara Resources Inc., 2026; Meteoric Resources NL, 2026; Serra Verde Group, 2024; St George Mining Limited, 2026; Viridis Mining and Minerals Limited, 2025). No independent duplicate scoring was performed; the coordinates therefore represent author-developed, evidence-informed judgments bounded by the stated cut-off date.

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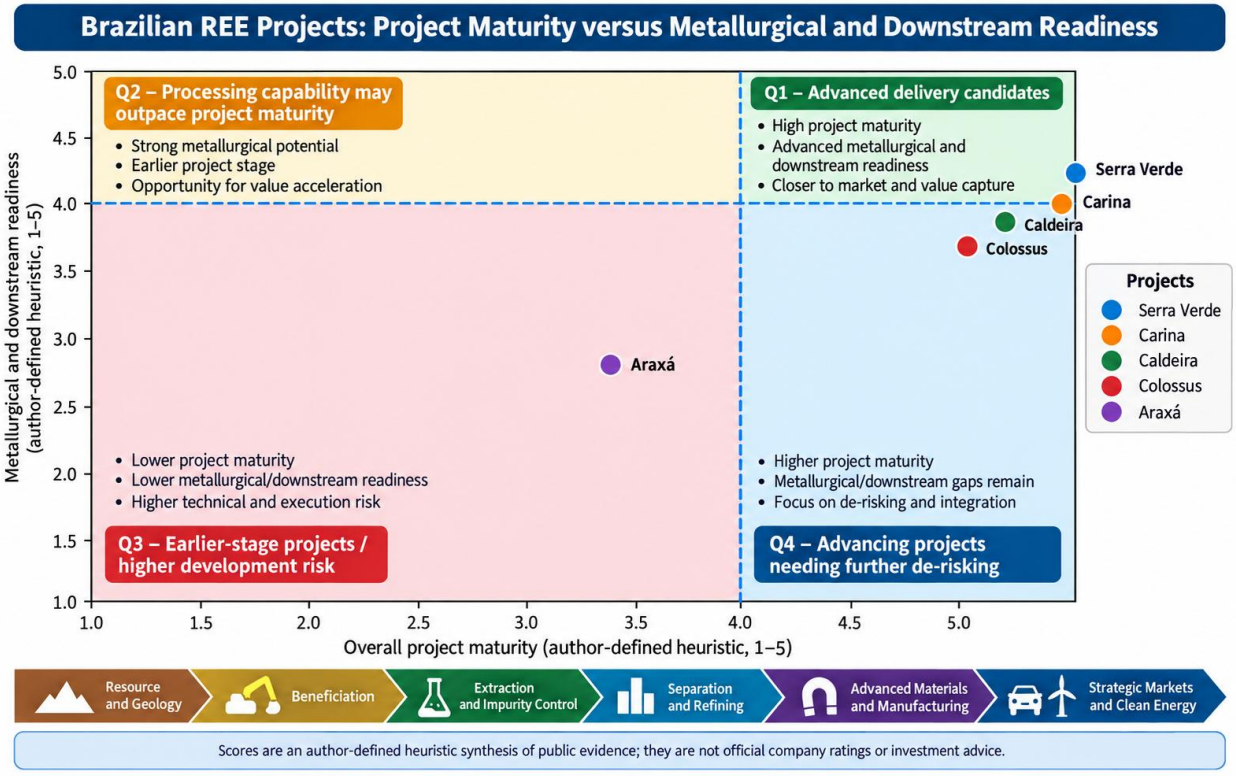

Figure 5. *Author-defined project maturity versus metallurgical and downstream readiness for selected Brazilian REE projects*

Note. Author-developed heuristic framework using the proposed TRL-REE logic and public evidence from Aclara Resources Inc. (2026), Meteoric Resources NL (2026), Serra Verde Group (2024), St George Mining Limited (2026), and Viridis Mining and Minerals Limited (2025). Both axes use bounded 1–5 heuristic scales; positions are qualitative and are not investment ratings.

The dispersion in Figure 5 illustrates the central R2V proposition: the largest geological option is not automatically the nearest industrial option. The decision-relevant question is which project can most reliably deliver a specification-compliant product through a permitted, financed, operable, and market-connected flowsheet. The two axes should therefore be interpreted as qualitative evidence summaries, not as company ratings or investment scores.

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12.3. Operationalizing the R2V Gap and the fifteen critical gaps

The R2V Gap can be decomposed into observable loss points rather than treated only as a qualitative metaphor. Table 9 identifies ten recurrent transitions where geological value can be lost before a qualified product reaches the market. The indicators are intended for screening and evidence auditing, not for additive scoring unless project-specific weights and uncertainties are independently justified.

Table 9 Operational decomposition of the Resource-to-Value Gap

R2V loss point	Measurable indicator	How value is lost	Evidence needed
Geological classification uncertainty	Resource category; spatial variance; confidence interval.	Inventory cannot be translated reliably into mineable feed.	Dated resource model and reporting basis.
Desorbable/exchangeable fraction loss	Desorbable REE / total REE by domain.	High assay overstates mild-leach recoverability.	Sequential extraction/desorption and mineralogical data.
Beneficiation loss	REE recovery to pre-concentrate; mass rejection; fines loss.	Valuable phases are discarded or diluted.	Size-by-size/mineral-by-mineral mass balance.
Leaching/extraction loss	Element-specific recovery to pregnant solution.	Contained magnet REE remains in residue.	Variability-tested extraction and kinetic data.
Impurity penalty	kg Fe+Al+Ca+Mg+P+Si dissolved per kg saleable REO.	Chemical demand, scaling, purification duty, and residues increase.	PLS composition and reagent/residue balance.
Separation-yield loss	Element recovery through separation and polishing.	High-value NdPr/DyTb is lost in raffinate, bleed, or off-spec fractions.	Stage-wise mass balance, purity, and recycle losses.
Product-specification rejection	Fraction meeting agreed impurity/particle/customer specification.	Produced REE cannot realize intended product netback.	Certificate/specification and customer qualification data.
ESG/permitting delay	Permitting duration; water/residue/radiological closure status.	Time, capital, and operating constraints delay or limit conversion.	Permits, water balance, residue and radiological plans.
Financing/offtake discount	Payability; contract coverage; cost/price sensitivity; financing status.	Technical product lacks bankable revenue or capital pathway.	Financing terms, offtake, payability, sensitivity analysis.

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Downstream manufacturing gap	Share of product converted to separated oxide/metal/alloy/magnet.	Chemical and manufacturing value is captured outside the domestic chain.	Qualified conversion capacity and customer-linked production data.

Note. Author-developed operationalization of the R2V Gap. Report indicators on consistent feed and saleable-product bases, and interpret them with project-specific uncertainty.

The synthesis identifies fifteen connected gaps: resource standardization and data reconciliation; mineralogical/deportment characterization; selective leaching; impurity management; domestic separation; Dy/Tb separation capability; magnet-grade oxide production; metal/alloy manufacturing; permanent-magnet scale-up; recycling; radioactive-residue management; techno-economic analysis (TEA) and LCA based on saleable REE rather than ore; skilled workforce and pilot infrastructure; price/offtake risk; and an integrated national REE database. These are not independent tasks. Better mineralogical characterization improves selective leaching; better selectivity reduces separation CAPEX; lower impurity load improves product qualification; and reliable product quality strengthens offtake and financing.

Table 10 converts the fifteen gaps into an action-oriented roadmap. Table 10 assigns each gap a preferred evidence metric and a development horizon so that research priorities can be connected to industrial milestones (Centro Brasileiro de Relações Internacionais, 2026; Centro de Tecnologia Mineral, 2025a; International Energy Agency, 2026; Mindreau, 2025).

Table 10 Critical gaps and proposed research/industrial roadmap for closing Brazil's REE Resource-to-Value Gap

Gap	Priority action	Evidence / KPI	Suggested horizon
1. Resource standardization	Reconcile national, USGS, JORC/NI 43-101 categories and dates	Traceable category + effective date + cut-off	Immediate
2. Mineralogy/deportment	Routine quantitative mineralogy and exchangeable-vs-bound REE profiling	REE deportment by horizon/mineral phase	Immediate–2028
3. Selective leaching	Optimize recovery against impurity mass transfer, not extraction alone	REE recovery + impurity/reagent intensity	Immediate–2029

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4. Impurity management	Design Fe-Al-Ca-Mg-P-Si removal into leach flowsheets	Impurity kg/kg saleable REO	Immediate–2029
5. Domestic separation	Build modular/pilot-to-commercial SX/IX capability	t/y separated REO qualified to customer spec	2027–2030
6. Dy/Tb separation	Develop dedicated HREE polishing and recovery	Dy/Tb recovery, purity, stage count	2027–2030
7. Magnet-grade oxide	Establish impurity and particle-specification qualification	Customer-qualified NdPr/Dy/Tb oxide	2027–2030
8. Metals/alloys	Scale oxide-to-metal and alloy routes	Qualified metal/alloy tonnes and yield	2028–2032
9. Permanent magnets	Industrialize powder, pressing, sintering, coating and QA	Qualified NdFeB magnet tonnes/y	2028–2032
10. Recycling	Build collection + direct/hydromet recycling loops	Recovered magnet REE from secondary feed	2028–2035
11. Radioactive residues	Standardize Th/U/Ra deportment and residue qualification	Activity balance + licensed residue route	Immediate–2030
12. TEA/LCA functional unit	Report cost/impact per saleable magnet REO/product	US$/kg and kg CO_2-e/kg qualified product	Immediate
13. Skills/pilot infrastructure	Maintain integrated continuous pilot facilities and training	Pilot hours, scale-up campaigns, trained specialists	Immediate–2030
14. Price/offtake risk	Use staged capacity, diversified customers and risk-sharing contracts	Payability, contract coverage, sensitivity ranges	Continuous
15. National REE database	Integrate geology, resources, metallurgy, ESG, production and projects	Versioned, public, traceable database	2026–2029

Note. Author-developed roadmap adapted from the evidence gaps identified by Centro Brasileiro de Relações Internacionais (2026), Centro de Tecnologia Mineral (2025a), International Energy Agency (2026), and Mindreau (2025).

The immediate priorities in Table 10 are deliberately upstream and midstream at the same time. Waiting for all mines to enter operation before building separation expertise would reproduce the R2V Gap. Conversely, constructing large downstream plants without qualified feed and committed customers could create stranded capacity. Coordinated modular development—

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integrated pilots, product campaigns, customer qualification, and staged capacity—is therefore the more resilient pathway.

12.4. Proposed mine-to-magnet roadmap toward 2030–2035

Figure 6 converts the synthesis into a staged mine-to-magnet roadmap. Figure 6 begins with data reconciliation and integrated pilots in 2026–2027, proceeds through mine ramp-up and MREC qualification, and then prioritizes domestic separation and magnet-grade oxides before larger metal/alloy and magnet manufacturing capacity. Recycling becomes progressively more important as the domestic stock of end-of-life magnets increases (Binnemans et al., 2013; Binnemans et al., 2021; Centro de Tecnologia Mineral, 2025a; Kaya, 2024; München et al., 2021; Author, 2026b).

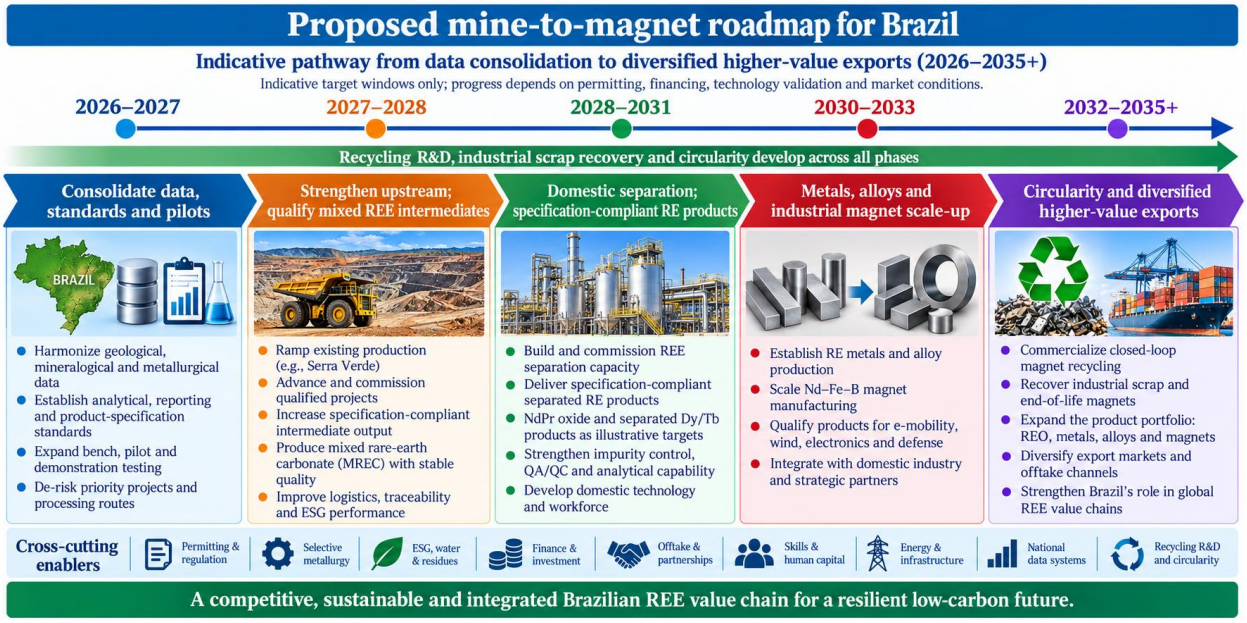

Figure 6. *Strategic roadmap for a Brazilian mine-to-magnet REE industry toward 2030–2035*
Note. Author-developed roadmap adapted from Centro Brasileiro de Relações Internacionais (2026), Centro de Tecnologia Mineral (2025a, 2025b), Binnemans et al. (2021), Kaya (2024), and the project-readiness evidence synthesized in this review.

The roadmap is intentionally adaptive. If domestic separation becomes competitive faster than expected, a larger share of MREC can remain in Brazil; if allied capacity offers better near-term

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economics, Brazilian producers can still use external separation while domestic pilot learning continues. The critical objective is to avoid locking the country permanently into the lowest-value links of the chain.

12.5. Limitations of the Review and Evidence Base

This review has several limitations that define the appropriate interpretation of its findings. First, it is a structured critical review rather than a formal systematic review or meta-analysis. Although the search was organized through predefined thematic domains and Boolean equations, the original workflow did not preserve database-specific retrieval logs or reason-specific exclusion counts at the resolution required for a retrospective PRISMA reconstruction. The revised manuscript therefore reports the verifiable corpus-level counts - 150 contemporary records screened and 60 retained - and does not invent database-specific or exclusion-reason totals that cannot be audited.

Second, the evidence base combines peer-reviewed literature with government documents, technical/reporting standards, institutional analyses, and company disclosures. This mixture is necessary for a rapidly changing project landscape, but the evidence types are not epistemically equivalent. Mechanistic interpretations were preferentially anchored to peer-reviewed research, whereas project status, feasibility milestones, planned capacities, resource statements, and offtake information sometimes required dated primary disclosures. Such disclosures may contain forward-looking assumptions and were not independently verified in this review.

Third, TRL-REE, BREE-VCR, the R2V Gap decomposition, RBV, and the project-readiness map are author-developed analytical frameworks. No independent duplicate coding or formal inter-rater reliability test was performed. Their purpose is structured evidence synthesis and screening, not project certification, reserve classification, feasibility determination, investment ranking, or valuation. The worked RBV example is hypothetical and should not be interpreted as a price forecast or project value.

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Fourth, the project, market, and policy landscape is unusually dynamic. All time-sensitive information was frozen at 9 September 2026; later changes in legislation, feasibility outcomes, financing, permitting, capacities, resources, offtake, or commercial operation cannot be inferred from this review. Finally, cross-project comparisons remain constrained by differences in reporting codes, cut-off grades, recovery definitions, product boundaries, resource categories, price assumptions, and study maturity. These limitations reinforce the review's central argument: geological inventory becomes strategically meaningful only when evidence is preserved across the full pathway from resource characterization to qualified saleable product.

13. Conclusions and Outlook

Brazil is moving from geological potential toward commercial relevance, but it has not yet completed the transition from a resource-rich jurisdiction to an integrated rare-earth industrial system. The 2020–2026 period marks a structural change: geological potential and limited production at the beginning of the decade gave way to Serra Verde's commercial production in 2024 and the rapid maturation of Caldeira, Carina, Colossus, and Araxá during 2025–2026. The next constraint is no longer discovery alone. It is the capacity to convert heterogeneous resources into selectively recovered, impurity-controlled, specification-compliant products and then into separated oxides, metals, alloys, magnets, and recycled feedstocks.

The Resource-to-Value Gap provides a more decision-relevant interpretation of Brazil's position than reserve ranking alone. Value can be lost at every transition: when resource categories are compared inconsistently; when mineral deportment is inadequately characterized; when extraction is optimized without selectivity; when mixed products leave the country without further separation; when environmental burdens are normalized to ore rather than saleable product; or when financing, offtake, and customer qualification lag technical development. Conversely, value is retained when geology, metallurgy, product specification, ESG performance, infrastructure, and market access are engineered as a single system.

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The strategic objective for 2030–2035 should therefore be staged integration rather than a binary choice between raw-material exports and complete self-sufficiency. Competitive mines and MREC production can expand while domestic separation, magnet-grade oxide qualification, metal/alloy conversion, and magnet manufacturing are developed modularly and linked to international customers. Recycling should grow in parallel as a secondary-feed platform. The strongest Brazilian REE strategy is one in which geological diversity creates multiple feed options, selective metallurgy protects recoverable value, midstream capability preserves technological choice, and global partnerships provide market depth. If these elements advance together, Brazil can convert geological abundance into durable mine-to-magnet industrial relevance.

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

Conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation: the sole author. Author-identifying information is withheld in the double-blind review version.

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Appendix A. Search Audit and Evidence Matrices

A.1. Core domain-specific search equations

The following equations reproduce the core Boolean architecture used to structure the review. Field tags were adapted to the scholarly discovery platform's syntax; quotation marks and Boolean operators were retained. Searches were supplemented by targeted retrieval of dated institutional and project primary sources for status claims.

B000 - Master Brazilian REE landscape

("rare earth elements" OR "rare earth element" OR "rare earths" OR REE OR REEs OR "rare earth oxide" OR REO OR TREO) AND (Brazil OR Brazilian) AND (resource OR resources OR reserve OR reserves OR deposit OR deposits OR occurrence OR project OR projects OR mine OR mining OR mineralogy OR beneficiation OR processing OR leaching OR extraction OR separation OR refining OR recovery OR metallurgy OR production OR magnet OR magnets OR market OR economic OR economics OR "supply chain")

B001 - Resources, reserves, deposits, production

("rare earth elements" OR "rare earths" OR REE) AND (Brazil OR Brazilian) AND (resource OR resources OR reserve OR reserves OR deposit OR deposits OR occurrence OR occurrences OR production OR mining)

B003 - Ionic adsorption clay

("rare earth elements" OR "rare earths" OR REE) AND (Brazil OR Brazilian) AND ("ion adsorption clay" OR "ion-adsorption clay" OR "ionic adsorption clay" OR "ionic clay" OR "weathered crust" OR regolith OR saprolite)

B006 - Mineralogy, deportment, beneficiation

("rare earth elements" OR "rare earths" OR REE) AND (Brazil OR Brazilian) AND (mineralogy OR mineralogical OR deportment OR speciation OR "host mineral" OR "host phase" OR liberation OR association) AND (beneficiation OR concentration OR flotation OR "magnetic separation" OR screening OR processing OR recovery)

B007 - Ionic clay leaching and ion exchange

("rare earth elements" OR "rare earths" OR REE) AND (Brazil OR Brazilian OR "South America") AND ("ion adsorption clay" OR "ionic clay" OR regolith OR "weathered crust") AND (leaching OR extraction OR desorption OR "ion exchange" OR "column leaching" OR "in situ leaching")

B009 - Extraction, impurities, selectivity

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("rare earth" OR REE) AND (Brazil OR Brazilian OR "ion adsorption clay") AND (leaching OR extraction) AND (selectivity OR impurity OR impurities OR "co-extraction" OR "co-dissolution") AND (aluminum OR iron OR silica OR calcium OR magnesium OR phosphorus OR thorium OR uranium)

B010 - Separation and Brazilian midstream gap

("rare earth" OR REE) AND (Brazil OR Brazilian) AND (separation OR purification OR refining OR fractionation OR "solvent extraction" OR "ion exchange" OR adsorption OR precipitation) AND (oxide OR carbonate OR MREC OR "mixed rare earth carbonate" OR "high purity")

B011 - Nd-Pr-Dy-Tb basket quality

("rare earth" OR REE OR REO OR TREO) AND (Brazil OR Brazilian) AND (LREE OR HREE OR neodymium OR Nd OR praseodymium OR Pr OR dysprosium OR Dy OR terbium OR Tb OR NdPr OR MREO) AND (grade OR recovery OR distribution OR composition OR basket OR value OR economic)

B015 - Economics and bankability

("rare earth" OR REE) AND (Brazil OR Brazilian) AND (economic OR economics OR feasibility OR bankability OR CAPEX OR OPEX OR financing OR investment OR offtake OR price OR revenue) AND (grade OR recovery OR basket OR NdPr OR Dy OR Tb OR "co-product" OR "by-product")

B017 - Market, geopolitics, industrial policy

("rare earth" OR REE) AND (Brazil OR Brazilian) AND (market OR geopolitics OR geopolitical OR policy OR "industrial policy" OR strategy OR sovereignty OR "critical minerals" OR "supply security" OR "supply chain" OR China)

B018 - Mine-to-magnet and readiness

("rare earth" OR REE) AND (Brazil OR Brazilian) AND ("mine to magnet" OR "mine-to-magnet" OR "value chain" OR "supply chain" OR downstream OR midstream OR integration) AND (mining OR processing OR separation OR refining OR oxide OR metal OR alloy OR magnet OR NdFeB)

B019 - Brazilian project pipeline

("rare earth" OR REE) AND (Brazil OR Brazilian) AND ("Serra Verde" OR "Pela Ema" OR Caldeira OR Carina OR Colossus OR Araxa OR Araxá) AND (resource OR mineralogy OR metallurgy OR processing OR leaching OR recovery OR pilot OR feasibility OR production)

Table S1 Source-selection flow and auditable corpus counts

Stage	Count	Audit note

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Contemporary working evidence pool identified/screened	150	2020-9 Sep 2026 working pool across scientific and targeted primary-source retrieval.
Contemporary sources retained and cited	60	Retained after relevance, traceability, duplicate/superseded-record, and claim-fit screening.
Contemporary records not retained	90	Aggregate only. Historical reason-specific counts were not archived and are not reconstructed retrospectively.
Foundational pre-2020 sources added	6	Added after screening to anchor beneficiation, SX, magnets, recycling, reporting standards, and critical-mineral availability.
Final cited corpus	66	60 contemporary + 6 foundational sources.

Note. Duplicate identification used DOI where available and normalized title plus author-year otherwise. Superseded project/policy releases were replaced by the most relevant dated source available before the cut-off.

Table S2 Evidence hierarchy and final source-type distribution

Evidence type	Final count	Primary role in the review	Interpretive boundary
Peer-reviewed scientific literature	49	Mechanisms, geology/mineralogy, beneficiation, leaching, separation, ESG/LCA, economics, recycling.	Preferred basis for scientific/mechanistic claims.
Government/statistical sources	5	Official reserves/production, policy and legislative status.	Authority for dated official status; definitions may differ across institutions.
Technical/reporting-standard sources	2	National geological synthesis and reporting-code definitions.	Technical context; not equivalent to a project-specific independent audit.
Company disclosures	5	Project resources, PFS/DFS/FS, operating milestones, planned production and product route.	Primary project-status evidence; forward-looking assumptions are not independently verified here.

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Institutional/policy reports	5	Supply-chain bottlenecks, national programs, policy strategy and international outlook.	Used for institutional/strategic context, not substitute for process evidence.
Author-developed synthesis	n/a	R2V, TRL-REE, BREE-VCR, RBV, readiness maps and roadmap.	Heuristic analytical synthesis; no independent duplicate scoring.

Note. Counts sum to 66 cited external sources; author-developed frameworks are not counted as external evidence.

Table S3 Source-level evidence matrix for major frameworks, project claims, and roadmap elements

Claim/framework	Primary supporting evidence	Source type / role
Brazil reserve and production reconciliation	Agência Nacional de Mineração (2025). U.S. Geological Survey (2026); Joint Ore Reserves Committee (2012)	Official statistics + reporting terminology.
R2V problem definition	Collerson et al. (2025); Fritz et al. (2023); Huang & Xie (2025); O'Brien & Alonso (2025)	Peer-reviewed value/process/economic evidence; author synthesis.
TRL-REE project maturity	Aclara Resources Inc. (2026). Meteoric Resources NL (2026); Serra Verde Group (2024); St George Mining Limited (2026); Viridis Mining and Minerals Limited (2025)	Dated primary project-status evidence; heuristic classification.
BREE-VCR dimensions	Centro Brasileiro de Relações Internacionais (2026). Ilankoon et al. (2022); International Energy Agency (2026); project technical disclosures	Institutional + peer-reviewed + project evidence; author matrix.
RBV logic	Collerson et al. (2025); Fritz et al. (2023); Heim & Vander Wal (2023); O'Brien & Alonso (2025)	Peer-reviewed basket/recovery/economic context; author screening equation.
Ionic-regolith recovery mechanisms	Azimi (2025); Bishop et al. (2024); Ding & Azimi (2024);	Peer-reviewed mechanistic evidence.

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	He et al. (2023); Russo et al. (2025); Wu et al. (2023)	
Beneficiation/mineralogy constraint	Antoniassi et al. (2020); Cheng et al. (2024); Jordens et al. (2013); Santana & Botelho (2022)	Peer-reviewed mineralogy/beneficiation evidence.
Impurity-control bottleneck	Judge & Azimi (2020); Liu et al. (2025); Wang et al. (2025)	Peer-reviewed process/LCA evidence.
Midstream separation bottleneck	Dewulf et al. (2022); El Ouardi et al. (2023); Guo et al. (2026); Xie et al. (2014); CETEM (2025a, 2025b)	Peer-reviewed separation + Brazilian program evidence.
NdPr vs Dy/Tb distinction	Dewulf et al. (2022); Gutfleisch et al. (2011); Guo et al. (2026); Heim & Vander Wal (2023)	Peer-reviewed separation, magnet and demand evidence.
Serra Verde status	Serra Verde Group (2024); Agência Nacional de Mineração (2025)	Company operating disclosure + national source.
Caldeira status	Meteoric Resources NL (2026)	Dated DFS/project disclosure.
Colossus status	Viridis Mining and Minerals Limited (2025)	Dated PFS/project disclosure.
Carina status	Aclara Resources Inc. (2026)	NI 43-101 feasibility disclosure.
Araxá status	St George Mining Limited (2026); Biondi & Braga (2023)	Dated project MRE + peer-reviewed geological context.
ESG/water/radiological performance	Guedes et al. (2026); Hamza et al. (2026); Langkau & Erdmann (2021); Schreiber et al. (2021); Wang et al. (2025)	Peer-reviewed ESG/LCA/radiological evidence.
Recycling loop	Binnemans et al. (2013, 2021); Kaya (2024); München et al. (2021); Author (2026b)	Foundational/current peer-reviewed evidence; self-citation anonymized.
Roadmap - separation/oxides/metals/magnets	Centro Brasileiro de Relações Internacionais (2026); CETEM (2025a, 2025b); International Energy Agency (2026)	Institutional capability-gap and program evidence.
Roadmap - data, skills, financing/offtake	Bogmans et al. (2026); Ilankoon et al. (2022); Mindreau (2025); project disclosures	Institutional/peer-reviewed market and bankability evidence.

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Note. The matrix identifies the principal evidence supporting each major synthesis element; it is not intended to duplicate every citation appearing in the narrative.

Table S4 Due-diligence treatment of principal company disclosures

Project/source	Disclosure date / effective basis	Study or reporting basis	Use in this review	Independent-verification boundary
Serra Verde / Pela Ema	11 Jan 2024 commercial-production release	Operating milestone/company release	Commercial start-up and product-route status.	Operating statement accepted as dated primary status evidence; no independent plant audit performed.
Caldeira	31 Jul 2026 DFS; 2026 resource/reserve updates	ASX disclosure; JORC-2012 resource/reserve basis as reported by company	DFS scale, production basis, resource and development stage.	Figures not independently re-estimated; forward-looking economics treated as company assumptions.
Colossus	9 Jul 2025 PFS; Jan 2025 MRE	ASX PFS; JORC Mineral Resource basis as reported by company	Resource, MREO/TREO, PFS stage and product route.	No independent verification of resource model or PFS economics.
Carina	13 Apr 2026 filing; FS effective 20 Mar 2026	NI 43-101 Technical Report & Feasibility Study	Resource/reserve, product strategy, MREC purity, planned production and stage.	Technical report prepared by qualified independent contributors, but this review did not reproduce their due diligence.
Araxá REE-Nb	11 Aug 2026 updated MRE	ASX/JORC-2012 MRE basis as reported by company	Contained TREO, NdPr and Nb2O5 inventory and development status.	Contained inventory is not treated as equivalent to reserve, recovery, or project value.

Note. Corporate disclosures are used only for date-bound project-status claims. Forward-looking statements, economic assumptions, and company-defined targets are not treated as peer-reviewed evidence or investment conclusions.

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