INTELLECTUAL PROPERTY AS AN AXIS OF TECHNOLOGICAL SOVEREIGNTY IN THE RARE EARTHS VALUE CHAIN: EVIDENCE FROM MINAS GERAIS

PROPRIEDADE INTELECTUAL COMO EIXO DE SOBERANIA TECNOLÓGICA NA CADEIA DAS TERRAS RARAS: EVIDÊNCIAS DE MINAS GERAIS

LA PROPIEDAD INTELECTUAL COMO EJE DE LA SOBERANÍA TECNOLÓGICA EN LA CADENA DE LAS TIERRAS RARAS: EVIDENCIAS DE MINAS GERAIS

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ABSTRACT

Rare earth elements constitute strategic mineral resources due to their application in technology-intensive sectors such as renewable energy, electric mobility, advanced electronics, and defense, assuming growing geopolitical relevance. Although Brazil holds significant geological potential for these elements, especially in Minas Gerais, its insertion into global value chains remains concentrated in the initial stages of mineral exploitation, revealing a mismatch between resource abundance and technological mastery. In this context, the article analyzes the role of the Industrial Property Law (Law No. 9,279/1996) as an instrument of technological sovereignty, linking the debate to international dynamics of control over critical minerals. A qualitative, exploratory, and analytical-descriptive approach is adopted, based on bibliographic and documentary review on geology, processing technologies, innovation, and territorial governance. The results indicate that the strategic value of rare earths depends more on the mastery of critical technological processes than on mere mineral extraction. It is concluded that technological sovereignty requires an integrated institutional arrangement, articulating innovation, intellectual property, and public policies oriented toward sustainable development.

Keywords: Rare Earths. Intellectual Property. Technological Sovereignty. Geopolitics of Strategic Resources. Minas Gerais.

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RESUMO
As terras raras constituem recursos minerais estratégicos devido à sua aplicação em setores intensivos em tecnologia, como energias renováveis, mobilidade elétrica, eletrônica avançada e defesa, assumindo crescente relevância geopolítica. Embora o Brasil detenha expressivo potencial geológico desses elementos, especialmente em Minas Gerais, sua inserção nas cadeias globais de valor permanece concentrada nas etapas iniciais da exploração mineral, revelando um descompasso entre abundância de recursos e domínio tecnológico. Nesse contexto, o artigo analisa o papel da Lei da Propriedade Industrial (Lei nº 9.279/1996) como instrumento de soberania tecnológica, articulando o debate às dinâmicas internacionais de controle dos minerais críticos. Adota-se abordagem qualitativa, exploratória e analítico-descritiva, com base em revisão bibliográfica e documental sobre geologia, tecnologias de beneficiamento, inovação e governança territorial. Os resultados indicam que o valor estratégico das terras raras depende do domínio de processos tecnológicos críticos, mais do que da simples extração mineral. Conclui-se que a soberania tecnológica requer um arranjo institucional integrado, articulando inovação, propriedade intelectual e políticas públicas orientadas ao desenvolvimento sustentável.

Palavras-chave: Terras Raras. Propriedade Intelectual. Soberania Tecnológica. Geopolítica dos Recursos Estratégicos. Minas Gerais.

RESUMEN
Las tierras raras constituyen recursos minerales estratégicos debido a su aplicación en sectores intensivos en tecnología, como las energías renovables, la movilidad eléctrica, la electrónica avanzada y la defensa, adquiriendo una creciente relevancia geopolítica. Aunque Brasil posee un significativo potencial geológico de estos elementos, especialmente en Minas Gerais, su inserción en las cadenas globales de valor permanece concentrada en las etapas iniciales de la explotación minera, lo que revela un desajuste entre la abundancia de recursos y el dominio tecnológico. En este contexto, el artículo analiza el papel de la Ley de Propiedad Industrial (Ley n.º 9.279/1996) como instrumento de soberanía tecnológica, articulando el debate con las dinámicas internacionales de control de los minerales críticos. Se adopta un enfoque cualitativo, exploratorio y analítico-descriptivo, basado en una revisión bibliográfica y documental sobre geología, tecnologías de beneficio, innovación y gobernanza territorial. Los resultados indican que el valor estratégico de las tierras raras depende más del dominio de procesos tecnológicos críticos que de la simple extracción minera. Se concluye que la soberanía tecnológica requiere un arreglo institucional integrado, que articule innovación, propiedad intelectual y políticas públicas orientadas al desarrollo sostenible.

Palabras clave: Tierras Raras. Propiedad Intelectual. Soberanía Tecnológica. Geopolítica de los Recursos Estratégicos. Minas Gerais.

1 INTRODUCTION

Rare earth elements (REEs) are a group of chemical elements formed by lanthanides, plus yttrium and scandium, whose unique physicochemical properties make them strategic inputs for the contemporary high-tech industry. Despite the historical name, these elements are not geologically scarce, but they have a high dispersion in the Earth's crust and chemical complexity that makes it difficult for them to be concentrated, separated and individually purified, which explains their economic and geopolitical relevance (Abrão, 1994; Castor & Hedrick, 2006). Lanthanid contraction, a phenomenon responsible for the similarity of ionic rays and oxidation states, imposes significant technological challenges to the beneficiation and refining processes, increasing costs and requiring advanced technological solutions (Abrão, 1994).

In recent decades, the intensification of global demand for REEs has been driven by the expansion of strategic sectors such as renewable energy, electric mobility, information technology, defense, industrial catalysis, and high-performance electronic devices. Permanent magnets based on neodymium, dysprosium and praseodymium, catalysts, phosphors, special alloys and optical components illustrate the centrality of these elements for the energy transition and for the so-called low-carbon economy (Chakmouradian & Wall, 2012; Haque et al., 2014).

In this context, the concentration of global production and processing, historically dominated by China, has transformed rare earths into strategic assets associated with the economic security and technological sovereignty of national states.

Brazil stands out in this scenario for having one of the largest known reserves of rare earths in the world, with a significant increase in estimates based on the incorporation of deposits located, above all, in the states of Minas Gerais and Goiás. Recent studies indicate that the country has come to occupy a prominent position in the global ranking of reserves, although it still has a marginal participation in the production of oxides and, mainly, in the aggregation of technological value (DNPM, 2014; Souza, Nascimento & Giese, 2019)

Such asymmetry reveals a recurring paradox of the Brazilian mineral economy: geological abundance coexisting with technological and industrial dependence.

Minas Gerais plays a central role in this debate, due to the occurrence of deposits associated with alkaline and alkaline-carbonatite complexes, such as those of Araxá and the Poços de Caldas Plateau, as well as ionic adsorption clays and mineral tailings with potential for secondary recovery. The technological characterization of these resources demonstrates that, although the levels are significant, economic viability depends on the mastery of

sophisticated extraction, separation, and purification processes, including hydrometallurgical and biohydrometallurgical routes (Antoniassi, 2017; Gupta & Krishnamurthy, 2005).

Recent literature also points to the advancement of technologies based on bioleaching and biosorption as more environmentally sustainable alternatives, capable of reducing energy consumption and waste generation, expanding the potential for the use of low-grade ores (Barmettler et al., 2016; Amin et al., 2014; Souza, Nascimento & Giese, 2019)

These technological advances, however, highlight the need for legal protection of the knowledge generated along the rare earths production chain. Innovative processes of beneficiation, solvent separation, bioleaching, biosorption, development of advanced materials and industrial applications constitute strategic intangible assets, whose misappropriation can compromise the national ability to compete in technology-intensive global value chains.

In this sense, the **Intellectual Property Law (Law No. 9,279/1996)** emerges as a fundamental instrument for the protection of inventions, utility models and industrial secrets related to the mineral sector, functioning as a mechanism to encourage innovation, technology transfer and technological sovereignty.

Unlike an approach focused exclusively on primary exploitation, protection via intellectual property allows for the articulation of mining, science, technology and innovation, transforming natural resources into platforms for technological development.

In the case of rare earths, this articulation is particularly relevant, since the economic value of these elements is less associated with the extraction itself and more with the mastery of the technological processes that enable their application in high value-added products.

Thus, the absence of intellectual protection strategies tends to perpetuate patterns of external dependence, while their adoption strengthens the capacity of the State and national companies to retain value, stimulate applied research and consolidate technological skills.

In this context, this article analyzes the role of the **Intellectual Property Law as an instrument of technological sovereignty,** based **on the case of rare earths in Minas Gerais**, articulating geological, technological and institutional evidence. It is based on the assumption that technological sovereignty does not result only from the possession of natural resources, but from the ability to transform them into protected knowledge, industrial innovation and sustainable territorial development.

2 THEORETICAL BACKGROUND

2.1 RARE EARTHS AS STRATEGIC MINERAL RESOURCES

Rare earth elements (REEs) are strategic mineral resources due to their transversal application in sectors that are intensive in technology and innovation. Although they are not rare from a geological point of view, their economic exploitation is conditioned by mineralogical, geochemical and technological factors that make their individual separation and purification difficult, significantly increasing production costs (Abrão, 1994; Castor & Hedrick, 2006). The chemical similarity resulting from lanthanide contraction imposes relevant metallurgical challenges, requiring sophisticated technological routes to obtain oxides and metals of high purity, an indispensable condition for advanced industrial applications (Gupta & Krishnamurthy, 2005).

The strategic importance of rare earths has intensified in recent decades due to the energy transition, the digitalization of the economy and the growth of so-called green industries. Permanent magnets, catalysts, batteries, optical and electronic components illustrate the centrality of these elements for production chains considered critical to the economic and technological security of national states (Chakmouradian & Wall, 2012; Haque et al., 2014). In this context, the high concentration of global production and refining, historically led by China, reinforced the geopolitical character of rare earths, transforming them into instruments of economic and technological power.

In Brazil, although reserves are significant, the country's insertion in the global value chain remains limited, focusing mainly on the extraction and export of raw materials or low value-added products. Such a scenario reveals a dissociation between geological potential and technological capacity, configuring a pattern of dependence that compromises industrial and technological sovereignty (DNPM, 2014; Souza, Nascimento & Giese, 2019).

2.2 MINAS GERAIS AND THE TECHNOLOGICAL POTENTIAL OF RARE EARTHS

Minas Gerais occupies a central position in the geography of rare earths in Brazil, housing important deposits associated with alkaline and alkaline-carbonatite complexes, such as Araxá and the Poços de Caldas Plateau, as well as occurrences in ionic adsorption clays and mineral tailings that can be reused. Technological characterization studies show that these geological environments have relevant potential, but require high technical mastery to make their exploration economically viable (Antoniassi, 2017).

The literature points out that the main rare earth bearing minerals in the Brazilian territory include monazite, bastnasite, xenotime, and ionic adsorption clays, each with specific challenges related to radioactivity, low grade, mineralogical complexity, and environmental

impacts (Abrão, 1994; Haque et al., 2014). Because of these limitations, conventional extraction methods, based predominantly on energy-intensive hydrometallurgical routes and chemical reagents, present economic and environmental constraints, especially for low-grade ores (Gupta & Krishnamurthy, 2005).

In this context, recent advances in biotechnology applied to mining have been pointed out as promising alternatives. Bioleaching and biosorption techniques, based on the action of microorganisms and organic metabolites, have demonstrated potential for the recovery of rare earths from mineral matrices and residues, with lower energy consumption and lower environmental impact (Barmettler et al., 2016; Amin et al., 2014; Brisson et al., 2015). Studies conducted in Brazil indicate significant recovery efficiencies, especially in processes involving monazite, clays, and industrial waste, reinforcing the role of technological innovation in the sustainable viability of the production chain (Souza, Nascimento & Giese, 2019)

2.3 INDUSTRIAL PROPERTY, INNOVATION AND TECHNOLOGICAL SOVEREIGNTY

The transformation of strategic mineral resources into lasting competitive advantages depends, fundamentally, on the ability to generate, protect and exploit technological knowledge. In this sense, industrial property assumes a central role by guaranteeing temporary exclusivity over inventions, processes and industrial applications, encouraging investments in research, development and innovation. Law No. 9,279/1996, by disciplining invention patents and utility models, constitutes an essential legal instrument for the protection of intangible assets associated with the rare earth chain.

In the mineral sector, protection through industrial property does not focus on the natural resource itself, but on the technological processes that enable its efficient, sustainable and economically competitive exploitation. Innovative routes for processing, separation, purification, bioleaching, biosorption and development of advanced materials are strategic assets that can be protected, whose misappropriation can compromise national technological autonomy. Thus, the absence of intellectual protection strategies tends to perpetuate the country's peripheral position in the global value chain, while their adoption strengthens technological and industrial sovereignty.

From this perspective, technological sovereignty is not limited to the availability of natural resources, but involves the ability to control critical technologies, retain economic value, and guide territorial development strategically. In the case of Minas Gerais, the articulation between geological potential, technological innovation and protection via industrial property is fundamental to break with the traditional extractive model and promote a more qualified insertion of the state and the country in the knowledge economy.

This article aims to analyze the role of the **Industrial Property Law (Law No. 9,279/1996)** as an instrument of **technological sovereignty**, based **on the case of rare earths in Minas Gerais**, considering the strategic relevance of these elements for technology- and innovation-intensive production chains. Initially, it seeks to characterize rare earths as strategic mineral resources, highlighting their chemical properties, industrial applications and geopolitical importance, according to the specialized literature (Abrão, 1994; Chakmouradian & Wall, 2012; Haque et al., 2014).

Next, it is intended to examine the geological and technological potential of rare earth occurrences in the territory of Minas Gerais, with emphasis on alkaline and alkaline-carbonatitic complexes and the technical limitations associated with their economic use (Antoniassi, 2017; Souza, Nascimento & Giese, 2019).

The study also aims to discuss the main technological challenges related to the processes of extraction, separation and purification of these elements, including the emerging role of hydrometallurgical and biohydrometallurgical routes as more sustainable alternatives (Amin et al., 2014; Barmettler et al., 2016).

Finally, it seeks to evaluate the importance of protecting innovations associated with the rare earths production chain through industrial property, showing how the adoption of technological protection strategies can contribute to the reduction of external dependence, the aggregation of value to the mineral resource and the strengthening of technological sovereignty and territorial development in Minas Gerais.

The Role of the Geological Survey of Brazil in the Identification and Valuation of the Potential of Rare Earths and Strategic Minerals

The **Geological Survey of Brazil (SGB)** has played a central role in the production of the geoscientific knowledge necessary to guide public policies, investments and development strategies related to strategic mineral resources, especially **rare earths**. According to a note released by the SGB itself in 2025, Brazil holds about **23% of the world's reserves of rare earths,** estimated at approximately 21 million tons, positioning itself as one of the main global holders of these critical elements, although national production remains extremely limited, with about 20 tons produced in 2024, representing less than 1% of world production that year (SGB, 2025).

This diagnosis highlights one of the main challenges for the implementation of a strategic mineral policy: the discrepancy between the **abundant geological potential and the technological and institutional capacity to transform this potential into production and competitive added value.** The SGB CEO emphasizes that it is necessary to expand the geological knowledge of the national territory and "transform the enormous geological

potential of strategic mineral resources into exploitable and well-known mineral reserves", overcoming technological, logistical and infrastructure limitations (Brasil Mineral, 2025).

Within this agenda, the SGB conducts systematic geological mapping research and evaluation of occurrences in several Brazilian states, including programs such as the evaluation of potentials in unprecedented areas, for example, in **the Parnaíba Basin**, where dozens of new occurrences associated with rare earth elements and uranium were identified, indicating additional possibilities for expanding Brazilian mineral knowledge.

Other efforts include initiatives in Goiás, Tocantins, Bahia, Paraná, São Paulo, Amazonas, Roraima, Rondônia, Pará, and Piauí, as part of projects that aim to identify and characterize promising mineralogical regions in different geological frameworks, expanding the database necessary for public and private decision-making.

The SGB's work also includes the production of collaborative technical reports, such as the publication "Brazil's role in the Global Agenda for Critical and Strategic Minerals", the result of a partnership with institutions such as CEBRI, IBRAM, CETEM and Cenergia (Coppe/UFRJ). This report combines analysis of national demand, supply potential, and the positions that the country can occupy in the energy transition and in global supply chains, reinforcing the need to diversify the supply and processing of critical minerals as a way to reduce geopolitical risks and strengthen Brazil's presence in strategic markets, Mineral Connection (2025).

These geoscientific efforts assume crucial relevance when articulated with the broader normative and public policy debate, especially in light of legislative initiatives such as the National Policy on Critical and Strategic Minerals, approved by the Economic Affairs Commission (CAE) of the Federal Senate, which aims to establish guidelines for the processing and internal industrialization of these minerals. In this sense, the data produced by the SGB will not only subsidize the formulation of more robust mineral policy instruments, but will also guide the allocation of resources for research, technological development and institutional training, essential elements to convert mineral potential into national productive and technological competences.

In addition, the ability to map occurrences and characterize deposits in different geological contexts contributes directly to territorial governance, by providing information that allows balancing the interests of economic development, environmental protection and social inclusion. This process is essential to ensure that the exploitation of rare earths occurs in a sustainable, responsible and integrated manner with regional development strategies that take into account local knowledge and the participation of affected communities.

As a whole, the performance of the Geological Survey of Brazil demonstrates that the production of geoscientific knowledge is an indispensable pillar for the formulation of effective public policies in the strategic mineral sector. By integrating cutting-edge research, detailed geological mapping, and information production for planning and decision-making, the SGB provides the necessary technical-scientific basis for Brazil to move towards broader technological sovereignty, reducing external dependence and expanding its participation in global critical mineral chains, in line with the environmental and technological challenges of the 21st century.

3 METHODOLOGY

This article adopts a **qualitative approach**, of an **exploratory and analytical-descriptive nature**, suitable for the investigation of complex phenomena that involve the articulation between strategic mineral resources, technological development and legal instruments for the protection of innovation. The choice of this approach is justified by the need to understand, in an integrated way, the geological, technological and institutional aspects related to rare earths in Minas Gerais, as well as the role of the Industrial Property Law in the promotion of technological sovereignty.

From the point of view of technical procedures, the research is based on **a bibliographic and documentary review,** carried out from national and international secondary sources. The literature review focused on classic and contemporary works on rare earth chemistry and technology, extractive metallurgy, biotechnology applied to mining, and economics of strategic mineral resources, with emphasis on the works of Abram (1994), Gupta and Krishnamurthy (2005), Castor and Hedrick (2006), Chakmouradian and Wall (2012), Haque et al. (2014), Antoniassi (2017) and Souza, Nascimento and Giese (2019). These studies provided the theoretical basis for understanding the chemical properties, the technological challenges of extraction and the recent trends of innovation in the rare earth production chain.

The documentary analysis included technical and institutional reports from public agencies and research centers, such as the National Department of Mineral Production/National Mining Agency, the Center for Mineral Technology (CETEM) and specialized publications that deal with the reserves, production and technological challenges associated with rare earths in Brazil, with emphasis on the state of Minas Gerais. Normative and legal documents were also examined, especially **Law No. 9,279/1996 (Industrial Property Law),** in order to identify the legal protection mechanisms applicable to technological innovations developed in the field of mining and mineral processing.

The spatial focus of the research is concentrated in the **state of Minas Gerais**, due to its geological and strategic relevance in the Brazilian context of rare earths, especially with regard to the alkaline and alkaline-carbonatitic complexes and the recent initiatives of technological characterization and reuse of mineral waste. Such a delimitation allows for a more in-depth analysis of the relationship between territory, natural resources and innovation policies.

The analysis of the collected data was carried out through **qualitative content analysis**, seeking to identify convergences, gaps and tensions between the existing geological potential, the stage of technological development of the extractive routes and the legal framework for the protection of industrial property. This analysis made it possible to discuss how the protection of technological innovations associated with rare earths can contribute to the aggregation of value to the mineral resource, to the reduction of external dependence and to the strengthening of technological sovereignty.

The recent literature on rare earths in Brazil has emphasized the existence of a "Brazilian paradox", characterized by the coexistence between an expressive geological endowment and a still incipient production, especially with regard to the higher value-added stages of the production chain. In this sense, Júlio Edstron Secundino Santos has highlighted that, although Brazil is among the countries with the largest known reserves of rare earths, its insertion in global chains remains limited to the export of raw materials or low-processing products, which compromises the strategic use of these elements in the context of energy transition and sustainable development. This reading reinforces the idea that mineral abundance, by itself, does not automatically translate into technological sovereignty, and that it is necessary to articulate industrial policies, innovation and knowledge protection.

In addition, Fernando Landgraf points out that the country has not only relevant natural resources, but also installed technical-scientific capacity, capable of sustaining more ambitious strategies for the rare earths sector. For the author, the central challenge lies in overcoming institutional, regulatory and coordination obstacles between public and private actors, in order to transform geological wealth into a competitive industrial base. This perspective dialogues directly with the notion of long-term strategic planning defended by contemporary science, technology, and innovation policies.

In the field of applied technology, the work of André Nunis, a researcher at the Institute for Technological Research (IPT), shows concrete advances in the construction of a national chain for the production of permanent magnets made of rare earths, such as the MAGBS project. These initiatives demonstrate that Brazil already has the technical competence to advance in strategic segments of the production chain, especially those associated with the

high-tech industry, such as electric motors, renewable energy generation and electric mobility. The existence of these projects reinforces the importance of protection via industrial property, as a way to safeguard the knowledge generated and avoid its external appropriation.

From a sociopolitical perspective, Elaine Santos, in an article published in *Jornal da USP* in December 2025, analyzes the debate on rare earths in light of structural inequalities and the risks of reproduction of a primary-export model. The author draws attention to the need to incorporate social, environmental, and territorial criteria into mineral exploration strategies, preventing the race for critical minerals from reinforcing regional asymmetries and compromising the rights of local communities. This approach broadens the technical debate by incorporating sociological and institutional dimensions into the discussion on technological sovereignty.

In the field of geological research, teams linked to federal universities such as UFSM, UFRGS and Unipampa, in Rio Grande do Sul, and the Federal University of Roraima have identified new occurrences and relevant concentrations of rare earths in different geological contexts. These studies reinforce the role of public research institutions in expanding national geoscientific knowledge and reducing exploratory uncertainties, an essential element for the strategic planning of the mineral sector and for the formulation of evidence-based public policies.

At the international level, recent research has also contributed to deepening the understanding of the technological and geopolitical challenges associated with rare earths. Juan Diego Rodriguez-Blanco and Melanie Maddin of Trinity College Dublin published in 2024 a study that revisits the formation models of bastnäsite, one of the main rare earth bearing minerals, demonstrating the complexity of the geochemical processes involved and questioning previously accepted simplified models. These scientific advances reinforce the idea that the technological mastery of the rare earth chain depends on frontier research and the constant updating of geological and metallurgical models.

The geopolitical dimension of the topic is widely discussed by Kalim Siddiqui, who, in a 2025 report, analyzes the emerging tensions around critical minerals and rare earths, with emphasis on the high concentration of supply and processing in China. The author argues that this concentration generates strategic vulnerabilities for import-dependent countries, intensifying trade disputes and encouraging national policies of reindustrialization and security of supply, a scenario in which Brazil occupies a potentially strategic position, as long as it advances in policies of value addition and innovation.

Additionally, international studies in the area of ecotoxicology, conducted by authors such as R. R. Samal, Ż. Arciszewska, C. Figueiredo and M. Andrade, have evidenced the

environmental impacts associated with the dispersion of rare earths in aquatic ecosystems and their interaction with biomacromolecules. These works reinforce the need for environmentally responsible extraction and processing technologies, as well as regulatory frameworks capable of mitigating socio-environmental risks, a central aspect for the social legitimacy of mineral policies.

Finally, strategic reports prepared by authors such as Karl Friedhoff, from the *Chicago Council on Global Affairs*, and by institutions such as the International Energy Agency (IEA) and the London School of Economics (LSE) highlight that the future of the global rare earths market will depend on the diversification of supply chains, the strengthening of national industrial policies, and continuous investment in science, technology and innovation. These analyses converge in pointing out that countries endowed with mineral resources, such as Brazil, will only be able to occupy a relevant position in this scenario if they are able to articulate scientific knowledge, legal protection, strategic planning and territorial governance.

The methodology adopted allowed the integration of different fields of knowledge geosciences, mineral technology, biotechnology and industrial property law in an interdisciplinary way, consistent with the objectives of the study and with the level of depth required in a scientific academic article.

Legislative Advances in the National Policy on Critical and Strategic Minerals Implications for Rare Earths and Technological Sovereignty

On December 9, 2025, the **Committee on Economic Affairs (CAE)** of the Federal Senate approved the report that establishes the **National Policy on Critical and Strategic Minerals,** through the substitute for *Bill No. 4443/2025*, authored by Senator Renan Calheiros, with a favorable opinion from the rapporteur Senator Esperidião Amin (PP-SC). This approval represents a relevant institutional milestone for the development of the strategic minerals chain in Brazil, including rare earth elements, and reaffirms the need for structured public policies that promote the aggregation of value, mineral processing in the national territory and the security of the national industry in the face of contemporary geopolitical challenges (SENADO FEDERAL, 2025).

The proposal approved in the CAE provides for instruments aimed at stimulating the processing and industrialization of critical minerals in the country, with the determination that a relevant part of the ore extracted, such as **up to 80% of rare earths, be processed and industrialized in Brazilian territory,** as a way to **ensure control over mineral wealth and prevent the export exclusively of raw inputs (**FEDERAL SENATE, 2025).

This requirement for national processing directly articulates the technical-legal debate on the importance of transforming mineral resources into **technologies, processes and**

products with higher added value, overcoming a historical pattern of commodity exports and reinforcing the **country's technological and industrial sovereignty.**

The substitute also includes the periodic updating of the **Brazilian List of Critical and Strategic Minerals,** the creation **of Mineral Transformation Processing Zones (ZPTMs),** specific tax and credit incentives, financing mechanisms, public-private partnerships and research consortia, all interpreted as indispensable instruments to promote technological innovation and competitiveness of the mineral sector (FEDERAL SENATE, 2025). These instruments align with recent debates that advocate the need **for long-term strategic planning for critical minerals,** integrating research and development (R&D), technological capacity building, and industrial policies that go beyond simple geological exploitation, promoting **sustainable and inclusive innovation strategies.**

In addition, the proposition approved in the CAE amends provisions of **the Mining Code** with the objective of accelerating the return of unexplored areas and reducing speculative mechanisms for withholding mining rights, which may contribute to a more efficient and transparent territorial governance structure, reducing administrative obstacles and promoting greater predictability for mining and industrial transformation projects (FEDERAL SENATE, 2025). This regulatory dimension reinforces the importance of a legal framework that articulates **strategic planning, governance, and sustainability,** creating conditions for Brazil to develop technological and productive competencies essential to the twenty-first century.

From a political-institutional point of view, the approval of the substitute by the Senate is part of a broader context of public policy formulation that recognizes the role of critical minerals in the **energy transition, economic security, and the dispute over global value chains.** The agenda reflects not only national interests, but also international pressures and expectations regarding Brazil's positioning as a reliable and sustainable supplier of strategic minerals for advanced technologies, contributing to overcoming structural vulnerabilities and external dependencies already identified in the rare earths sector (BNAMERICAS, 2025).

Finally, the approval in the CAE indicates a significant advance for the implementation of a **regulatory framework that combines control of natural resources with stimulation of technological innovation and legal protection of innovative processes,** elements that, when articulated with instruments such as the **Industrial Property Law,** have the potential to transform the competitiveness profile of the Brazilian mineral sector. By promoting domestic industrialization and encouraging the development of extraction, processing and recycling technologies, including in synergy with socio-environmental sustainability

measures, this National Policy signals a concrete unfolding of the debate on **technological sovereignty, value aggregation and sustainable territorial development** in Brazil.

4 RESULTS AND DISCUSSION

A critical reading of the bibliographic and documentary set analyzed allows us to affirm that the "strategic value" of rare earths does not derive only from the existence of deposits, but above all from the ability to **convert geological potential into technological competence,** with institutional, environmental and legal support. In practical terms, this means that the Brazilian comparative advantage tends to remain incomplete as long as the country does not robustly master the stages of **concentration, separation, purification and transformation** into industrial inputs (oxides and metals) and, mainly, into **goods with higher added value.** such as alloys and permanent magnets, critical components for the energy transition (ABRÃO, 1994; CASTOR; HEDRICK, 2006; CHAKMOURADIAN; WALL, 2012; HAQUE et al., 2014).

From a technical point of view, the literature confirms that a relevant part of the cost and industrial risk is associated with the very nature of REEs: the similarity of chemical behavior between lanthanides linked to lanthanide contraction imposes complex separation and refining routes, usually intensive in energy and reactants, with direct effects on economic viability and environmental control requirements (ABRÃO, 1994; GUPTA; KRISHNAMURTHY, 2005).

This finding is particularly relevant for Minas Gerais, whose importance stands out for deposits associated with alkaline and alkaline-carbonatitic complexes (such as Araxá) and for mineralogical and metallogenetic contexts that require detailed characterization to guide technological and economic decisions (ANTONIASSI, 2017; TRAVERSA et al., 2001; NEWMANN; MEDEIROS, 2015; ISSA FILHO; LIMA; SOUZA, 1984).

In this context, a central interpretative result of the study is the identification of a **"middle of the chain" bottleneck** in Brazil: even if there are relevant reserves, the consolidation of a national chain depends less on the mining itself and more on the industrial domain of processing and separation, as well as on the creation of transformation capacities into strategic products.

This gap helps to explain the "paradox" reiterated in the recent literature: **geological opulence coexisting with low industrial production and external dependence**, especially in the technological stages with the highest density of knowledge (DNPM, 2014; SOUZA; NASCIMENTO; GIESE, 2019).

In the field of technological alternatives, the findings discussed reinforce that conventional routes do not need to be abandoned, but **complemented and modernized** by solutions with less impact and greater efficiency.

The reviewed literature indicates that biohydrometallurgical routes such as **bioleaching and biosorption** have been gaining ground due to their potential to reduce energy consumption and chemical load, in addition to increasing the feasibility of using low-grade and waste matrices, bringing mining closer to a circular economy logic (AMIN et al., 2014; BARMETTLER et al., 2016; BRISSON; ZHUANG; ALVAREZ-COHEN, 2015; SOUZA; NASCIMENTO; GIESE, 2019).

In this sense, the discussion points out that technological innovation is not only an "efficiency improvement", but a structuring element to reconcile competitiveness with sustainability, especially in scenarios where environmental and social aspects influence access to markets and financing.

Still in this axis, the research shows that the **recycling of REEs** tends to consolidate itself as an inevitable strategic dimension. Recovery from industrial waste, electrical and electronic equipment and permanent magnets can reduce vulnerabilities related to external volatility and geopolitical asymmetries of supply, functioning as a complement to primary mining and as a vector of innovation in separation processes.

The absence of a robust and coordinated national policy for rare earth recycling emerges as a relevant institutional weakness, as it limits the construction of resilient chains and hinders the use of urban mining as a technological-industrial asset.

At the institutional and informational level, the analysis of the role of the Geological Survey of Brazil (SGB) shows that **geoscientific knowledge is a strategic infrastructure of the State.** By disclosing estimates and clarifying the mismatch between reserves and production, the SGB supports an evidence-based public policy agenda, drawing attention to the need to transform geological potential into technically known and economically exploitable reserves, overcoming technological, logistical and infrastructure limitations (SGB, 2025; BRASIL MINERAL, 2025; MINERAL CONNECTION, 2025). For Minas Gerais, this reinforces the importance of integrating mapping, mineralogical characterization and technological evaluation as preconditions to reduce uncertainties and guide choices about processing routes and industrial projects.

The legal-institutional dimension appears as a decisive vector of the results: **Law No. 9,279/1996** becomes especially relevant because the capture of value in rare earths occurs, to a large extent, in the sphere of **processes** (separation, purification, hydrometallurgical and

biohydrometallurgical routes), **advanced materials** (alloys, magnets, catalysts) and **industrial applications.** that is, in the domain of codifiable and securable knowledge.

The discussion indicates that the absence of industrial property strategies tends to perpetuate technological dependencies, while their adoption creates conditions for value retention, investment attraction, and strengthening of the national capacity for innovation and technology transfer.

At this juncture, the results of the study gain political density by dialoguing with the recent legislative agenda. The approval, in the CAE of the Federal Senate, of the report that establishes the National Policy on Critical and Strategic Minerals (within the scope of the substitute for PL No. 4,443/2025) signals a relevant inflection: the policy proposes instruments to stimulate processing and industrialization in the national territory and explains the guideline to expand the internal processing of critical minerals, articulating incentives, processing zones, financing mechanisms, and periodic updating of the list of strategic minerals (FEDERAL SENATE, 2025).

In analytical terms, it is a movement that tries to shift Brazil from a predominantly primary-export position to an **industrialization strategy guided by technological sovereignty**, capable of internalizing stages of greater added value.

In addition, the provision of regulatory adjustments, including measures aimed at rationalizing the use of mining areas and addressing speculative retentions, tends to directly influence the governance of the sector and the predictability of industrial and ST&I projects, a central aspect when it comes to critical minerals, whose attractiveness depends on institutional stability and long-term planning (FEDERAL SENATE, 2025).

The debate also connects to international pressures for safe and sustainable supply chains, in which Brazil is often seen as a potential supplier of strategic minerals; this expectation can be an opportunity (investment attraction) or a risk (reprimarization), depending on the institutional design and the degree of domestic value added (BNAMERICAS, 2025).

Thus, the discussion converges on a key point: it is not enough to "have" rare earths; it is necessary to govern them as a State policy, articulating a robust geoscientific base, a ST&I agenda oriented to the bottlenecks of separation, refining, recycling and development of advanced materials, economic and regulatory instruments capable of encouraging internal industrialization, a consistent industrial property strategy to protect and scale the knowledge generated, and territorial governance that reduces conflicts, distribute benefits and strengthen regional capacities, especially in Minas Gerais.

Why the Immediate Environmental Licensing of Rare Earths in Minas Gerais is a Wrong Decision

The repeated postponement of the vote on the environmental licensing of large rare earth exploration projects in Minas Gerais reveals more than mere procedural obstacles: it exposes structural weaknesses in the decision-making model adopted for the management of a strategic mineral resource whose exploitation involves environmental, social and technological risks that are still insufficiently understood in the Brazilian context. In this sense, within the scope of Civil Inquiry No. 1.22.000.004558/2022-65, the Federal Public Prosecutor's Office issued MPF/MG Recommendation No. 30, of September 3, 2025, directing the competent state agencies, notably the State Secretariat for the Environment and Sustainable Development, the State Environmental Foundation and the State Council for Environmental Policy to suspend the analysis of the environmental licensing processes related to the Colossus projects, in Poços de Caldas, and Caldeira, in the municipality of Caldas. The recommendation was based on the insufficiency of independent technical studies and the need to deepen the analysis of the potential environmental and social impacts of these projects, whose complexity goes beyond the parameters ordinarily used in licensing processes.

The MPF's action is expressly anchored in the precautionary principle, according to which the absence of scientific certainty cannot be invoked as a justification for the adoption of decisions potentially causing serious or irreversible damage. Among the concerns highlighted in the inquiry and the recommendation are the environmental and nuclear risks associated with the extraction of rare earths often linked to the presence of radioactive elements, as well as the water impacts resulting from the movement of large volumes of clay and the use of chemical leaching techniques. Such practices can compromise strategic aquifers, such as the Poços de Caldas Alkaline Aquifer, the main source of supply in the region, in addition to producing cumulative effects on ecosystems interconnected to the Atlantic Forest biome. In addition, the MPF highlighted the possibility of violation of the right to prior, free and informed consultation of potentially affected traditional peoples and communities, in line with grounds already adopted in similar recommendations involving lithium mining in Minas Gerais. Notwithstanding the clarity of the ministerial orientation, the maintenance of some of these processes on the Copam voting agenda generated institutional controversies and successive decision-making postponements, evidencing tensions between the logic of economic acceleration and the constitutional requirements of environmental protection and collective rights. (RÁDIO DA FAMÍLIA, 2025).

In addition, factors such as the proximity of deactivated nuclear areas such as the Caldas Decommissioning Unit (UDC) of Indústrias Nucleares do Brasil and the absence of broad participation of local populations, including traditional communities, aggravate the complexity of the licensing process. The MPF also pointed out the need for regionalized studies and the performance of a Strategic or Integrated Environmental Assessment for the Poços de Caldas Plateau, instead of a fragmented licensing focused on isolated projects, which does not capture the synergistic effects of multiple mining operations in the same region (RACISMO AMBIENTAL, 2025).

The attempt to move quickly with licensing represents a mistake from an environmental, social and territorial governance point of view, as it underestimates the complexity of the risks involved and ignores the importance of a more robust and transparent deliberative process. Permit approval is mistakenly assumed to be a mere bureaucratic step, when in fact it can trigger lasting impacts on water quality, local biodiversity, public infrastructure, and the livelihoods of communities directly affected.

From a strategic point of view, this stance also ignores what economic analysts emphasize about the sector: the central challenge for Brazil is not only the release of areas for exploration, but the sustainable and technological transformation of reserves into an effective supply of strategic products. As highlighted in recent analyses, the country's main difficulty in converting its high geological potential into concrete economic or technological power does not stem from legal restrictions on foreign access or concession per se, but from gaps in processing technology, refining, integrated industrial policy, and investment in innovation (CNN Brasil, 2025)

Moving forward in a hasty manner with exploration licenses, without a solid scientific basis, effective environmental monitoring mechanisms, guarantees of broad consultation with affected populations and clear strategies for mitigating cumulative impacts, can result not only in significant environmental damage, but also in socioeconomic costs that burden the State and weaken the legitimacy of mineral public policies. The example of Minas Gerais illustrates that the race for rare earths cannot be treated as an end in itself, but must be articulated with agendas of sustainable development, technological sovereignty and respect for the constitutional principles of protection of the environment and the rights of traditional communities.

In short, the decision to repeatedly postpone environmental licensing reflects not only the necessary prudence in the face of scientific uncertainties, but also the need to rethink the way Brazil and Minas Gerais in particular equate the exploration of critical minerals with the

protection of environmental, social and territorial assets. Without this balance, hasty licensing policies can become more of a strategic mistake than a lever for development.

In short, the repeated postponement of environmental licensing for the exploration of rare earths in Minas Gerais should not be interpreted only as an administrative obstacle, but as an indication of the need to rethink, in a structural way, the model adopted for the management of critical minerals in Brazil. The hasty granting of licenses, dissociated from technological, institutional and strategic criteria, tends to reproduce a historical pattern of primary exploitation, with high environmental and social risks and with limited capacity to retain value in the territory.

In this context, licensing, when treated as a mere authorizing instrument, can become a strategic error, as it favors the immediate exploitation of resources without guaranteeing counterparts in terms of innovation, industrialization and regional development.

Geopolitics of Strategic Resources: The Attack on Venezuela and the Impacts on the Global Oil and Rare Earths Market

The intensification of geopolitical tensions involving Venezuela, especially after the political, economic, and diplomatic offensive conducted by the United States starting in 2025 and deepening in early 2026, highlights the centrality of strategic natural resources in the contemporary reorganization of global value chains. Although the international debate has focused predominantly on the immediate effects on the global oil market, recent analyses indicate that the consequences of this conflict go beyond the energy sector, also reaching critical minerals, such as rare earths, essential inputs for the energy transition, the high-tech industry, and defense systems (G1, 2026).

Venezuela holds one of the largest oil reserves in the world and occupies a historical position of relevance in global energy geopolitics. The adoption of unilateral measures and external offensive actions, often justified under discourses of hemispheric security and resumption of regional influence – associated with the so-called Monroe Doctrine – caused instability in international energy markets. As a result, there was an increase in oil prices, an increase in volatility, and an increase in the perception of systemic risk, leading large economies to reinforce strategies for diversifying suppliers and supply routes, with emphasis on China's strategic repositioning in the face of the uncertainty scenario (G1, 2026; AGÊNCIA BRASIL, 2025).

According to financial market analyses, the U.S. offensive against Venezuela has also produced relevant indirect effects on peripheral and emerging economies, including Brazil. The increase in global uncertainty impacted investment flows, exchange rates, commodity prices, and industrial expectations, reinforcing the vulnerability of countries dependent on the

import of strategic inputs and the export of primary products (INFOMONEY, 2026). These chain effects show how geopolitical shocks in the energy sector tend to radiate impacts to other strategic segments of the global economy.

In this context, rare earths assume an increasingly sensitive role in international geopolitical dynamics. Like oil, these elements are not only strategic because of their geological existence, but above all because of the technological and political control of the critical stages of their production chain. The global concentration of beneficiation, separation, purification, and industrial application activities confers significant geoeconomic power to countries that master these technologies, making the others vulnerable to supply interruptions, trade pressures, and exogenous geopolitical decisions. The instability observed in Venezuela, added to global trade and technological disputes, reinforces the trend of securitization of critical mineral chains, bringing them closer and closer to the logic historically applied to oil (AGÊNCIA BRASIL, 2025).

For Brazil, and particularly for Minas Gerais, this international scenario works as a strategic alert. The historical dependence on primary-export models, associated with the fragility in the protection of innovation and the absence of integrated industrial policies, creates the risk of reproduction, in the rare earths sector, of the same logic of structural vulnerability observed in the Latin American oil market. The pressure for accelerated environmental licensing, dissociated from institutional, technological, and legal strengthening, tends to insert the country in a subordinate way in global value chains, promoting the transfer of knowledge, added value, and decision-making power to external actors (INFOMONEY, 2026).

Thus, the offensive against Venezuela should not be interpreted only as an isolated episode in energy geopolitics, but as a clear indication that strategic resources – are not the only ones – to be seen in the country. In this context, the articulation between mineral policy, technological innovation, and intellectual property protection emerges as an indispensable element to break historical cycles of dependence, allowing countries rich in natural resources to advance to higher stages of the value chains and reduce their exposure to external shocks and geopolitical decisions alien to their national interests

In light of the geopolitical scenario analyzed, especially the international tensions unleashed around Venezuela and their repercussions on global markets for strategic oil and minerals, this article argues that the technological sovereignty associated with rare earths should be conceived as an integrated and strategically oriented institutional arrangement.

In this arrangement, environmental licensing ceases to be a merely authorizing instrument and starts to play an inductive function, articulating with specific mechanisms for

the protection of the national interest. Such mechanisms include the requirement of processing and adding value in the national territory, the protection of innovations through industrial property instruments, the strengthening of territorial governance and the definition of safeguards capable of avoiding the exclusive appropriation of these resources by foreign capital. Only from an approach that transcends the traditional extractivist logic and that subordinates mineral exploration to clear industrial, scientific and technological policy objectives will it be possible to convert rare earths into structuring platforms for sustainable industrial, scientific and territorial development, compatible with a long-term project of national sovereignty and less vulnerable to external geopolitical shocks.

5 CONCLUSION

The analysis developed throughout this article shows that the debate on rare earths in Minas Gerais and in Brazil more broadly goes beyond the limits of geology and mining activity, inserting itself in the strategic core of science, technology, innovation and national sovereignty policies. In an international scenario marked by the intensification of geopolitical disputes, instability in global supply chains and high technological concentration, the mere availability of mineral reserves, although relevant, is insufficient to ensure technological autonomy, economic security or long-term development.

The results obtained indicate that the main Brazilian challenge lies in the ability to convert geological potential into endogenous technological and industrial skills. Such conversion presupposes mastery of the most sensitive and strategic stages of the rare earths chain: processing, separation, purification, recycling and the development of advanced industrial applications in which most of the added value and geoeconomic power is concentrated.

In this sense, technological innovation, including the development of advanced hydrometallurgical routes and biohydrometallurgical alternatives, emerges as a structuring element to reconcile economic competitiveness, environmental sustainability and reduction of external vulnerabilities.

The discussion also demonstrates that the governance of critical minerals cannot be dissociated from the legal-institutional framework. The Industrial Property Law plays a central role in the protection of the knowledge generated, in the prevention of the misappropriation of strategic technologies and in the creation of conditions for the retention of value in the national territory. The protection of innovations associated with rare earths shifts the axis from the exploitation of simple access to natural resources to the control of critical technologies, configuring itself as an indispensable pillar of a strategy of technological sovereignty.

At the political-institutional level, recent advances related to the National Policy on Critical and Strategic Minerals represent a relevant inflection in the Brazilian public agenda. However, the study maintains that such initiatives will only be effective if accompanied by robust coordination mechanisms between the Union, states and municipalities, by clear requirements for the aggregation of local value and by instruments capable of avoiding the exclusive capture of these resources by external interests. In this context, environmental licensing should not be understood only as an authorizing procedure, but as a strategic tool to induce technological development, innovation and sustainable territorial planning.

Finally, it is concluded that the construction of a consistent policy for rare earths in Minas Gerais requires an integrated and prospective approach, capable of articulating geoscientific knowledge, technological innovation, legal protection, territorial governance and long-term strategic planning. Only from this integration will it be possible to transform rare earths from a finite and vulnerable mineral asset into a structuring vector of industrial, scientific and sustainable development, aligned with national interests, technological sovereignty and the economic, environmental and geopolitical requirements of the 21st century.

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