v7.n9.2026

SCIENTIFIC JOURNAL - RECIMA21 ISSN 2675-6218

RARE EARTHS, ARTIFICIAL INTELLIGENCE AND GEOPOLITICAL POWER: PROPOSAL OF THE GEOENVIRONMENTAL CONVERSION MODEL OF TECHNOLOGICAL POWER (MCGPT) AND THE GEOENVIRONMENTAL INDEX OF STRATEGIC POTENTIAL FOR ARTIFICIAL INTELLIGENCE (IGPE-IA)

TERRAS RARAS, INTELIGÊNCIA ARTIFICIAL E PODER GEOPOLÍTICO: PROPOSIÇÃO DO MODELO DE CONVERSÃO GEOAMBIENTAL DO PODER TECNOLÓGICO (MCGPT) E DO ÍNDICE GEOAMBIENTAL DE POTENCIAL ESTRATÉGICO PARA INTELIGÊNCIA ARTIFICIAL (IGPE-IA)

TIERRAS RARAS, INTELIGENCIA ARTIFICIAL Y PODER GEOPOLÍTICO: PROPUESTA DEL MODELO DE CONVERSIÓN GEOAMBIENTAL DEL PODER TECNOLÓGICO (MCGPT) Y DEL ÍNDICE GEOAMBIENTAL DE POTENCIAL ESTRATÉGICO PARA LA INTELIGENCIA ARTIFICIAL (IGPE-IA)

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e799024
https://doi.org/10.47820/recima21.v7i9.9024

PUBLISHED: 09/2026

ABSTRACT

The expansion of Artificial Intelligence (AI) increases the strategic relevance of rare earth elements, whose availability, processing, and integration into technological value chains influence state sovereignty and the configuration of geopolitical power. This study aims to analyze how rare earth elements, understood as strategic geoenvironmental assets, can be converted into industrial capacity, technological sovereignty, and geopolitical influence in the context of the global expansion of AI. The research adopts a qualitative, exploratory, and theoretical-conceptual approach, based on documentary research, an integrative literature review, thematic analysis, and interpretative synthesis. The results demonstrate that mineral reserves alone do not ensure strategic advantage, since technological power depends on the articulation of sustainable extraction, processing, advanced manufacturing, scientific capacity, AI infrastructure, cybersecurity, and governance. Documentary evidence indicates increasing concentration of the value chain in higher-value-added stages, particularly refining and magnet manufacturing. As original contributions, the study proposes the Geoenvironmental Conversion Model of Technological Power (MCGPT), which systematizes the transformation of geoenvironmental resources into technological power, and the Geoenvironmental Index of Strategic Potential for Artificial Intelligence (IGPE-IA), conceived as a multidimensional framework for future comparative assessment. It is concluded that technological sovereignty depends less on isolated mineral availability than on the systemic, sustainable, and institutional capacity to convert resources into strategic technological capabilities.

KEYWORDS: *Rare earth elements; Artificial Intelligence; Technological sovereignty.*

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SCIENTIFIC JOURNAL - RECIMA21 ISSN 2675-6218

RESUMO
A expansão da Inteligência Artificial (IA) amplia a relevância estratégica das terras raras, cuja disponibilidade, processamento e integração às cadeias tecnológicas influenciam a soberania dos Estados e a configuração do poder geopolítico. Este estudo objetiva analisar como as terras raras, compreendidas como ativos geoambientais estratégicos, podem ser convertidas em capacidade industrial, soberania tecnológica e influência geopolítica no contexto da expansão mundial da IA. A pesquisa possui abordagem qualitativa, caráter exploratório e finalidade teórico-conceitual, fundamentando-se em pesquisa documental, revisão bibliográfica integrativa, análise temática e síntese interpretativa. Os resultados demonstram que a posse de reservas minerais, isoladamente, não assegura vantagem estratégica, uma vez que o poder tecnológico depende da articulação entre extração sustentável, processamento, manufatura avançada, capacidade científica, infraestrutura de IA, segurança cibernética e governança. Evidências documentais mostram a crescente concentração da cadeia nas etapas de maior valor agregado, especialmente refino e fabricação de ímãs. Como contribuições originais, propõem-se o Modelo de Conversão Geoambiental do Poder Tecnológico (MCGPT), que sistematiza a transformação dos recursos geoambientais em poder tecnológico, e o Índice Geoambiental de Potencial Estratégico para Inteligência Artificial (IGPE-IA), concebido como *framework* multidimensional para futura avaliação comparativa. Conclui-se que a soberania tecnológica depende menos da disponibilidade mineral isolada do que da capacidade sistêmica, sustentável e institucional de converter recursos em competências tecnológicas estratégicas.

PALAVRAS-CHAVE: Terras raras. Inteligência Artificial. Soberania tecnológica.

RESUMEN
La expansión de la Inteligencia Artificial (IA) aumenta la relevancia estratégica de las tierras raras, cuya disponibilidad, procesamiento e integración en las cadenas tecnológicas influyen en la soberanía de los Estados y en la configuración del poder geopolítico. Este estudio tiene como objetivo analizar cómo las tierras raras, entendidas como activos geoambientales estratégicos, pueden convertirse en capacidad industrial, soberanía tecnológica e influencia geopolítica en el contexto de la expansión mundial de la IA. La investigación adopta un enfoque cualitativo, exploratorio y teórico-conceptual, fundamentado en investigación documental, revisión bibliográfica integrativa, análisis temático y síntesis interpretativa. Los resultados demuestran que la posesión de reservas minerales, por sí sola, no garantiza una ventaja estratégica, ya que el poder tecnológico depende de la articulación entre extracción sostenible, procesamiento, manufactura avanzada, capacidad científica, infraestructura de IA, ciberseguridad y gobernanza. Las evidencias documentales muestran una creciente concentración de la cadena en las etapas de mayor valor agregado, especialmente el refinado y la fabricación de imanes. Como contribuciones originales, se proponen el Modelo de Conversión Geoambiental del Poder Tecnológico (MCGPT), que sistematiza la transformación de los recursos geoambientales en poder tecnológico, y el Índice Geoambiental de Potencial Estratégico para Inteligencia Artificial (IGPE-IA), concebido como un framework multidimensional para futuras evaluaciones comparativas. Se concluye que la soberanía tecnológica depende menos de la disponibilidad mineral aislada que de la capacidad sistémica, sostenible e institucional para convertir recursos en capacidades tecnológicas estratégicas.

PALABRAS CLAVE: *Tierras raras; Inteligencia Artificial; Soberanía tecnológica.*

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1. INTRODUCTION

The expansion of Artificial Intelligence is one of the most relevant technological transformations of the 21st century. Its incorporation into production processes, digital infrastructures, defense systems, public management, scientific research and decision-making mechanisms has changed the foundations of economic competitiveness and sovereignty of states. Unlike approaches that present AI as a predominantly logical, algorithmic or immaterial phenomenon, its operation depends on an extensive physical infrastructure, composed of data processing centers, semiconductors, telecommunications equipment, energy systems, electronic devices and high complexity industrial chains.

This materiality demonstrates that the expansion of the digital economy does not eliminate dependence on natural resources. On the contrary, it moves part of this dependence to minerals with physical and chemical properties essential to advanced technologies. This set includes rare earth elements — the fifteen lanthanides plus scandium and yttrium — used in permanent magnets, catalysts, optical components, electronic systems, metal alloys and other high performance applications (Balaram, 2019). The International Energy Agency acknowledges that these elements perform strategic functions in energy technologies, transport, Artificial Intelligence, aerospace industry, medicine and defense, which is why they have gone to the center of economic and technological security policies (IEA, 2026).

The designation “rare earth elements” does not necessarily mean that these elements are scarce in the earth’s crust. Their criticality largely stems from the occurrence in economically exploitable concentrations, the complexity of its chemical separation, the technological intensity of processing and the high geographical concentration of production chains. Therefore, the strategic analysis of these resources cannot be limited to the volume of existing reserves. It must consider the domain of the activities of extraction, processing, separation, refining, alloy production, manufacture of permanent magnets and integration of these materials into technological products.

The U.S. Geological Survey’s Mineral Commodity Summaries 2026 shows that the worldwide supply of rare earth remains marked by high productive concentration and different levels of external dependence. The report shows that the strategic position of countries varies not only according to their reserves and mineral production, but also according to the industrial and technological capacity installed along the value chain (USGS, 2026). This distinction is fundamental: the ownership of the underground resource does not automatically become technological autonomy or geopolitical influence.

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The relevance of this debate was expanded by the convergence between energy transition, economic digitization, industrial automation, Artificial Intelligence and new generation telecommunications. Kalantzakos (2020) argues that the decarbonization of the economy and the Fourth Industrial Revolution triggered an international race for continuous access to critical minerals, whose geographical concentration can produce new areas of tension and reorganize relations between industrial powers. This race is not only related to geological availability, but to the political, economic and technological control of networks that transform minerals into industrial components of high added value.

In this sense, rare earth elements have ceased to be treated exclusively as industrial inputs and have integrated policies of economic security, defense, technological innovation and national sovereignty. Empirical studies show that geopolitical risks affect prices, imported values and stability of rare earth markets. The analysis carried out by Fan, Omura and Roca (2023), from more than thirty years of Japanese import data, identified statistically significant relationships between geopolitical risk and rare earth market, especially the risks associated with China. This evidence reinforces the understanding that the supply of these elements does not only comply with conventional demand and price dynamics, but is subject to political decisions, trade restrictions and strategic disputes.

China is particularly relevant because it demonstrates the difference between having mineral resources and mastering a technological chain. Its position was built through long-term industrial policies, investments in processing, material production, development of technical skills and integration between mining and advanced manufacturing. The concentration of processing and component manufacturing allows the control exercised in the intermediate stages to be as or more strategic than the mineral extraction itself. Recent studies on the reorganization of rare earth chains indicate that tensions between China and the United States stimulate policies of diversification, industrial relocation and reduction of dependencies, although the construction of alternative chains involves high costs, technological barriers and long periods of maturation (Zhao, Cheng and Xu, 2026).

This reality supports the need for an expanded geoenvironmental interpretation. The concept of geoenvironmental asset adopted in this study is not limited to the physical existence of the ore. It covers the combination of territorial location, geological characteristics, economic viability, extraction conditions, ecological impacts, industrial infrastructure, environmental regulation, scientific knowledge and capacity to insert into technological chains. From this perspective, the strategic value of rare earth results from the interaction between nature, territory, technology, institutions and power.

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The environmental dimension is inseparable from this discussion. Although rare earth elements are used in technologies related to decarbonization and modernization of energy systems, their mining and processing can generate significant impacts. Among the main problems are high energy and water consumption, waste production, effluent generation, soil acidification, water contamination, metal dispersion and the presence of radioactive materials associated with certain mineral deposits. Edahbi, Plante and Benzaazoua (2019) observe that mining and refining produce significant amounts of solid and liquid waste and that the absence of adequate management techniques can cause contamination of drainage waters by rare earth elements and radioactive elements.

More recent studies confirm the permanence of this challenge. Han *et al.* (2025) identified structural tension between the efficiency of conventional extraction techniques and their environmental costs, including acidification, heavy metal contamination and risks associated with uranium and thorium present in certain ores. Diao *et al.* (2024), in turn, highlight that the expansion of rare earth technological applications occurs in parallel to environmental problems, market volatility and concentration of the production chain. This means that any strategy of mineral and technological sovereignty needs to incorporate sustainability criteria, life cycle assessment, environmental recovery, circular economy and social responsibility.

Lee and Wen (2018) demonstrated that rare earth production has a significant environmental footprint, but that the adoption of cleaner processes, emission control and technological improvements can reduce the industry's environmental costs. Sustainability, therefore, should not be understood as an external limitation to strategic capacity. It constitutes an internal variable of the continuity of the production chain itself, influencing its social legitimacy, regulatory stability, access to investments and resilience in the long term.

The circular economy also has the potential to reduce vulnerabilities, although it does not eliminate, in the short term, the need for primary extraction. Wang *et al.* (2024), in a model that integrated geological stocks and materials in use in ten regions between 2021 and 2050, identified imbalances between supply and demand, especially in heavy elements such as dysprosium and terbium. The authors concluded that circular strategies can increase secondary supply and reduce accumulated demand, contributing to a less polarized distribution of resources, but their implementation depends on international cooperation and governance mechanisms.

Mineral dependence associated with Artificial Intelligence should not, however, be interpreted as a linear relationship according to which every AI system directly contains large volumes of rare earth. The connection occurs in multiple layers. It involves the equipment that supports computing, storage, data transmission, power generation and management, cooling,

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automation, sensors, robotics, autonomous vehicles, aerospace systems and defense infrastructure. Thus, the expansion of AI contributes to increase the strategic value of industrial chains that depend on critical minerals and rare earth elements to varying degrees.

The IEA (2026) explicitly includes AI technologies among strategic rare earth applications. This association reveals that contemporary dispute is not restricted to software or algorithmic superiority. It achieves the ability to produce and maintain material infrastructure that makes it possible to train, operate and disseminate intelligent systems. The leadership in AI therefore depends on the interaction between scientific capital, energy availability, semiconductors, digital infrastructure, mineral resources, industrial capacity and security of supply chains.

In addition to economic competitiveness, AI has acquired increasing relevance for cybersecurity. Machine learning-based systems can be used to recognize abnormal patterns, audit automation, vulnerability identification, risk management, fraud prevention and digital infrastructure monitoring. Alves and Conceição (2025) demonstrate that the application of AI to compliance audits can increase the accuracy, continuity and preventive capacity of governance, risk and compliance processes. This contribution is relevant to the present study because it shows that the national capacity in AI is not only an economic advantage, but also a resource of institutional protection and digital infrastructure management.

However, the use of AI in critical environments requires transparency, governance, explainability and human oversight. Santana *et al.* (2026) observed that the increase in the performance of machine learning and deep learning models was accompanied by the expansion of algorithmic opacity, making it necessary to evolve the approaches of Explainable Artificial Intelligence. This discussion demonstrates that technological sovereignty does not only mean having advanced systems, but also understanding, governing, auditing and protecting their decision-making processes.

The articulation between critical minerals, AI and cybersecurity allows us to identify a more comprehensive strategic chain. Geoenvironmental resources support extraction and processing processes; they feed the materials and components industry; the industry provides the necessary infrastructure for technological development; and technological capacity can strengthen digital autonomy, cyber defense and international influence. However, the literature tends to investigate each of these dimensions separately.

Geoenvironmental studies often focus on mineral occurrence, viability of extraction and its ecological impacts. Economic research analyzes prices, supply, demand and commercial dependence. The works of International Relations emphasize competition between states, while

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the technological literature discusses Artificial Intelligence, semiconductors and digital transformation. There are still limited models capable of integrating, in a single explanatory structure, the transformation of geoenvironmental resources into industrial capacity, technological autonomy, cybersecurity and geopolitical power.

This fragmentation is the central gap in this research. Although it is already established that rare earth elements are relevant to technological industries and that their chains are subject to geopolitical risks, it remains insufficiently explained how different national capacities combine to convert mineral resources into strategic power. Geological availability alone does not explain technological leadership. Similarly, scientific excellence, without material and industrial safety, can remain dependent on external suppliers.

Thus, the study starts from the following thesis: “In the Age of Artificial Intelligence, rare earth elements ceased to constitute only strategic mineral resources and began to act as geoenvironmental assets capable of influencing technological sovereignty, cybersecurity and the redistribution of global geopolitical power.”

This thesis does not presuppose an automatic relationship between mineral reserves and state power. It is proposed that the geopolitical influence results from the ability to carry out a systemic conversion of the resource: transform mineral availability into sustainable extraction; extraction into processing; processing into industry of high technological intensity; industry in Artificial Intelligence infrastructure; digital capacity in cyber defense; and mastering these steps in technological sovereignty.

1.1. Research problem

From the identified gap, the following research problem is formulated: How does the ability to convert rare earth elements, understood as geoenvironmental assets, into industrial and technological infrastructure influence technological sovereignty, cybersecurity and the reconfiguration of global geopolitical power in the Age of Artificial Intelligence?

1.2. Research hypothesis

It is adopted as the main hypothesis that: The geopolitical power related to rare earth elements is not determined solely by the size of reserves or the volume of extraction, but by the integrated capacity of States to convert geoenvironmental resources into products of high technological value through sustainable extraction, industrial processing, scientific innovation, Artificial Intelligence infrastructure, cyber defense and strategic governance.

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Three complementary propositions derive from this main hypothesis:

P1: Countries that control the processing, component manufacturing and technological integration steps have greater strategic capacity than countries limited to the export of crude ore;

P2: Environmentally unsustainable practices reduce chain resilience, expand social and regulatory conflicts and compromise the continuity of strategic advantage;

P3: Technological sovereignty in the AI era depends on the combination of mineral security, industrial capacity, scientific domain, digital infrastructure, AI governance and cyber defense.

1.3. General objective

Analyzing how rare earth elements, understood as strategic geoenvironmental assets, can be converted into industrial capacity, technological sovereignty and geopolitical influence in the context of the global expansion of Artificial Intelligence.

1.4. Specific objectives

a) characterize the geological, environmental, industrial and technological importance of rare earth elements;

b) examine the geographical concentration of the components extraction, processing and manufacturing steps;

c) analyze the relationship between critical minerals, technological infrastructure and expansion of Artificial Intelligence;

d) discuss environmental sustainability as a condition of resilience of rare earth chains;

e) investigate the connections between Artificial Intelligence, technological sovereignty and cybersecurity;

f) identify the capabilities that allow to transform geoenvironmental resources into geopolitical influence;

g) propose the Geoenvironmental Conversion Model of Technological Power (MCGPT);

h) develop the Geoenvironmental Index of Strategic Potential for Artificial Intelligence (IGPE-IA) as a theoretical tool for comparative analysis.

1.5. Scientific justification and relevance

The scientific relevance of this study lies in the integration of fields that usually remain separate: Geoenvironmental Sciences, Mineral Economy, Industrial Policy, Artificial Intelligence,

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Cybersecurity and Geopolitics. The originality arises not only from the gathering of these themes, but from the proposition of an explanatory mechanism to demonstrate how natural resources can be converted into technological power.

This approach overcomes two reductionist interpretations. The former associates mineral power exclusively to the existence of reserves. The second treats AI as predominantly algorithmic capacity, disregarding its physical, energy and industrial infrastructure. The present study maintains that technological sovereignty depends on an integrated chain of capabilities and that failures at any stage can limit the conversion of geoenvironmental potential into strategic influence.

Research also has political and practical relevance. Governments can use the proposed model to identify bottlenecks in their value chains; scientific institutions can employ it to organize interdisciplinary programs; and companies can adapt it to the assessment of supply risks, sustainability and technological dependence.

1.6. Original contributions of the study

The first contribution consists of the proposal of the Geoenvironmental Conversion Model of Technological Power (MCGPT), structured in the following way:

Geoenvironmental resources

↓

Rare earth availability

↓

Sustainable extraction capacity

↓

Processing and separation capacity

↓

Advanced materials and components industry

↓

Technology and Artificial Intelligence Infrastructure

↓

Cyber defense capability

↓

Technological sovereignty

↓

Influence and geopolitical power

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The model assumes that each step works simultaneously as a value aggregation mechanism and potential bottleneck. A country may have significant reserves, but remain technologically dependent if it has no processing capacity. Similarly, it can have advanced industrial and scientific capacity, but remain vulnerable when it depends excessively on concentrated external suppliers.

The second contribution is the Geoenvironmental Index of Strategic Potential for Artificial Intelligence (IGPE-IA). The index is based on the dimensions of the MCGPT and is conceived in this article as a multidimensional analytical framework. Its purpose is to structure the evaluation of the potential of countries or regions to convert geoenvironmental resources into strategic technological capacity.

IGPE-IA is not presented at this stage as a statistically validated instrument or as a ranking of countries. Its contribution consists of the reasoned proposition of the dimensions, variables and relationships that can be operationalized and tested in future research. This delimitation avoids assigning the framework a measurement capacity that still depends on weighting, normalization, comparative application and empirical validation.

1.7. Scope of the study

The research focuses on rare earth relations, sustainability of the production chain, technological infrastructure, Artificial Intelligence, cybersecurity, technological sovereignty and geopolitics. It does not intend to perform detailed geological evaluation of specific deposits or economically estimate individual mining projects.

Nor does it maintain that rare earth elements are the only minerals relevant to the AI. Semiconductors and digital infrastructures depend on various materials such as copper, silicon, gallium, germanium, cobalt, nickel, lithium and graphite. The choice of rare earth elements stems from their unique properties, concentration of processing stages, relevance to advanced technologies and its analytical value to understand the relationship between natural resources and power.

1.8. Structure of the article

In addition to this introduction, the article is organized into four subsequent sections. Section 2 presents the theoretical framework on rare earth, mineral criticality, sustainability, Artificial Intelligence, cybersecurity, technological sovereignty and geopolitics. Section 3 explains the methodological path, including document analysis, integrative review and thematic synthesis.

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Section 4 brings together the results and discussion, developing the MCGPT and the IGPE-IA. Section 5 presents the final considerations, contributions, limitations and future validation agenda.

2. THEORETICAL FRAMEWORK

2.1. The evolution of the strategic importance of natural resources

The relationship between natural resources and political power follows the evolution of industrial societies. In different historical periods, specific raw materials have taken a central position in the organization of economies, in the territorial expansion of states and in the consolidation of military and technological advantages. Coal, iron, oil, uranium and critical minerals illustrate how certain resources can overcome the condition of commodities and become structuring elements of the international order (Yergin, 1991; Bridge, 2009; Klare, 2012).

During the First Industrial Revolution, mineral coal served as an energy base for mechanization, steel and railways. In the Second Industrial Revolution, oil took a decisive role in mobility, aviation, chemical industry and military projection. The history of oil shows that security of supply, location of reserves, transport infrastructure and refining capacity can change national alliances, conflicts and strategies (Yergin, 1991).

The digital economy did not eliminate the materiality of power relations. Energy transition, electrification, automation and AI increased the importance of materials with specific magnetic, optical and electrochemical properties. Kalantzakos (2020) argues that decarbonization and the Fourth Industrial Revolution triggered a race for access to critical minerals, while the IEA (2025, 2026) identifies strong concentration both in mining and refining of various strategic materials.

This change does not represent simply replacement of oil with critical minerals. It is a diversification of the material basis of power. Energy security remains relevant, but it coexists with mineral security, industrial security, digital security and scientific capacity. The State that relies on third parties to process materials, manufacture components, build digital infrastructures or operate strategic systems is exposed to risks that are not only explained by the geology of its territory.

From the geoenvironmental perspective, natural resources should be interpreted as part of socio-technical systems. Its value is not fixed: it depends on geological knowledge, extraction technology, infrastructure, regulation, environmental costs, social acceptance, logistics, processing capacity and market integration. This reading brings geography closer to the resources of the international political economy and allows us to understand why countries with large reserves can remain low-value exporters.

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Table 1. Historical evolution of the relationship between natural resources and power

Period	Dominant action	Technological basis	Geopolitical Expression
First Industrial Revolution	Coal and iron	Steam, steel and railway machinery	Industrialization and Imperial Expansion
20th Century	Oil and uranium	Transport, petrochemicals, aviation and nuclear energy	Energy security and military power
Digital-energy transition	Critical minerals and rare earth elements	Electrification, renewable energies, sensors, robotics and AI	Technological sovereignty and chain security

Source: author's preparation based on Yergin (1991), Bridge (2009), Klare (2012), Kalantzakos (2020) and IEA (2025).

2.2. Rare earth elements as geoenvironmental assets

The rare earth elements correspond to the fifteen lanthanides, usually considered together with scandium and yttrium due to geochemical similarities and industrial applications. Despite the denomination, several of these elements are not exceptionally scarce in the earth's crust. The main challenge is the low concentration in economically viable deposits and the difficulty of separating elements of similar chemical behavior (Balaram, 2019; Haque *et al.*, 2014).

Literature often distinguishes light and heavy rare earth elements. Classification may vary according to the criteria adopted, but it is useful because the elements present differences in abundance, mineralogy, availability and application. Neodymium and praseodymium are relevant for permanent magnets; dysprosium and terbium increase the performance of these magnets at high temperatures; europium, terbium and yttrium are used in phosphors and optical systems; lanthanum and cerium have wide use in catalysts, alloys and polishing (Balaram, 2019; Demir *et al.*, 2026).

Considering them geoenvironmental assets means integrating physical, territorial, ecological, economic, industrial and institutional dimensions. The asset is not only the mineral body, but the combination of reserve, ore quality, available technology, infrastructure, water and energy, licensing, waste treatment capacity, logistical access and social legitimacy. Criticality results from this combination and not from an isolated geological property (Nassar *et al.*, 2015).

Mining and processing can have significant impacts. Conventional methods require reagents, water and energy; certain deposits are associated with thorium and uranium; and separation steps can generate effluents and complex treatment wastes. Haque *et al.* (2014) and

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Edahbi *et al.* (2019) demonstrate that the sustainability of the chain requires evaluation of life cycle, waste management, recovery of areas and monitoring of water and soil.

The social dimension should also be considered. Mineral projects depend on relationships with communities, transparency, benefit sharing and regulatory compliance. The absence of these elements can provoke opposition, delays and loss of social licence to operate. Therefore, sustainability is not a peripheral variable; it directly interferes with productive continuity and the ability to convert a geological resource into a strategic advantage.

Table 2. Constitutive dimensions of rare earth elements as geoenvironmental assets

Dimension	Central questions	Strategic effect
Geological	Content, mineralogy, size and location of deposit	Defines physical potential and technical complexity
Environmental	Water, energy, waste, radioactivity and recovery	It affects costs, licensing and continuity
Industrial	Separation, refining, alloys, magnets and components	Determines value aggregation
Institutional	Regulation, industrial policy and governance	Coordinates investment and reduces uncertainty
Social	Participation, benefits and social licence	Conditions legitimacy and stability
Geopolitics	Dependency, trade and export controls	Converts concentration into influence

Source: elaboration of the author based on Nassar *et al.* (2015), Balaram (2019), Edahbi *et al.* (2019) and Demir *et al.* (2026).

2.3. Global value chains for critical minerals

The rare earth chain comprises successive and technologically distinct stages: prospecting, mining, concentration, chemical separation, production of oxides and metals, manufacture of alloys, magnets or other functional materials and incorporation into final products. Vulnerability does not depend only on the concentration of extraction; it can be even greater in refining, separation and component manufacturing (IEA, 2025; Demir *et al.*, 2026).

The IEA (2025) estimated that in 2024 the three largest countries concentrated 86% of mining and 97% of refining of the main elements used in permanent magnets. Even in scenarios with new projects, the concentration of refining remains high until 2030 and 2040. This shows that diversification of mines does not automatically lead to chain diversification.

The domain of intermediate steps generates cumulative advantages: scale, operational experience, supplier networks, availability of reagents, infrastructure, tacit knowledge and

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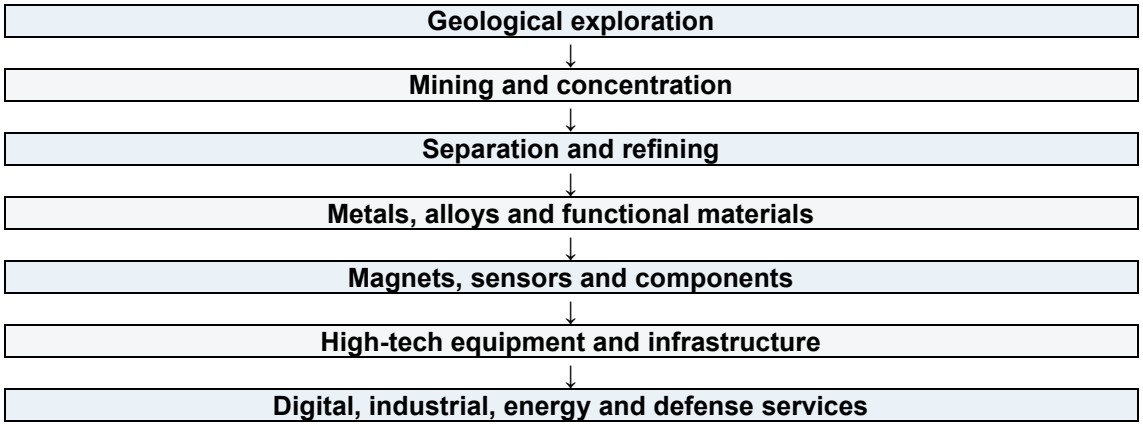
proximity to component manufacturers. New projects outside the dominant centers face high capital costs, price volatility, time-consuming licensing and difficulty in ensuring long-term buyers.

Resilience requires complementary strategies. These include geographical diversification, long-term contracts, strategic stocks, international partnerships, traceability, research in replacement, recycling and expansion of processing capacity. However, circularity has time limits: the amount of material available for recycling depends on the stock in use and the life of the products (Wang *et al.*, 2024).

The chain is also sensitive to political decisions. Export controls, sanctions, licensing requirements and restrictions on processing technologies can affect industries far beyond the mineral sector. The IEA (2026) demonstrates that extensive interruptions could compromise high-value sectors, including automobiles, electronics, defense and data centers.

Figure 1. Global chain of rare earth value



Source: elaboration of the author based on IEA (2025, 2026) and Demir *et al.* (2026).

2.4. Artificial Intelligence and its physical infrastructure

Artificial Intelligence is often described from computational algorithms, data and models. However, its operation depends on a material and energy infrastructure: semiconductors, servers, networks, storage systems, energy equipment, refrigeration, motors, sensors and automation devices. This physical base connects the digital economy to critical mineral chains.

Rare earth elements are not the only material set relevant to AI, and their function varies between equipment. They appear especially important in high performance permanent magnets, motors, actuators, disk drives, sensors, optical components, energy systems, telecommunications, robotics and data center auxiliary equipment. The relationship between AI

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and rare earth elements is therefore systemic and distributed, not a simple correspondence between an algorithm and a mineral element.

The IEA (2026) expressly included AI technologies and data centres among strategic applications exposed to risks in rare earth chains. The increase in the use of AI also increases the demand for energy, transmission infrastructure and refrigeration equipment, expanding the interdependence between digital security, energy security and mineral security.

From an economic point of view, leadership in AI depends on an ecosystem that combines research, capital, data, energy, chips, equipment, talent and industrial capacity. A country can develop advanced models and simultaneously remain vulnerable by relying on externally controlled components, materials or manufacturing technologies.

This materiality imposes a review of the concept of digital sovereignty. It is not enough to control data or have legislation. Autonomy requires the ability to operate infrastructure, ensure supply, maintain equipment, audit algorithms and respond to interruptions. Thus, the sovereignty of AI must be understood as socio-technical capacity based on physical and institutional resources.

Recent studies of public attention and academic visibility reinforce this convergence. The IICTEC Research Report No. 001/2026 identified that the global interest in AI began to reach, more clearly, semiconductors, GPUs, critical minerals and data centers (IICTEC, 2026). In a complementary analysis, Alves and Conceição (2026) found strong associations between public attention and academic visibility explicitly linked to AI for semiconductors, critical minerals and data centers, although they pointed out that the Google Scholar estimates do not represent exact publication counts.

Table 3. Materiality of the Artificial Intelligence infrastructure

AI Layer	Associated infrastructure	Material or industrial dependence
Training and inference	Servers, accelerators and storage	Semiconductors, metals, energy and cooling
Connectivity	Networks, cables, antennas and optical equipment	Electronic, optical and magnetic materials
Automation	Robots, motors, actuators and sensors	Permanent magnets and functional materials
Energy	Generation, transmission, UPS and cooling	Copper, magnets, power materials and equipment
Security	Monitoring, response and redundancy	Reliable infrastructure, maintenance and components

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Source: elaboration of the author based on IEA (2026), Balaram (2019) and Demir *et al.* (2026).

2.5. Cybersecurity and technological sovereignty

Technological sovereignty can be understood as the capacity of a society to decide, develop, operate, audit and protect technologies considered essential. The concept does not imply absolute self-sufficiency, but reduction of critical dependencies and maintenance of sufficient alternatives to preserve decision-making autonomy.

Cyber security integrates this capability because critical infrastructure, public services, industrial chains and defense systems depend on digital networks and applications. AI can expand the detection of anomalies, event correlation, audit automation and incident response. Alves and Conceição (2025) highlight the potential of AI to make compliance audits more continuous and preventive.

On the other hand, the adoption of AI creates risks related to opacity, bias, adverse attacks, data manipulation and platform dependency. Santana *et al.* (2026) observed that the advance in the performance of the models intensified the need for explanation and governance. Technological sovereignty, therefore, simultaneously requires innovation capacity and control capacity.

The response to these risks requires verifiable governance and research skills. Correia *et al.* (2026) systematize international standards and regulations applicable to AI governance, while Santana (2026) highlights AI-assisted techniques for analysis of authenticity, evidence tracking and investigation of misinformation. Together with the explanation discussed by Santana *et al.* (2026), these contributions show that technological autonomy depends on both operational capacity and transparency, auditability and human accountability.

Dependence on concentrated components or materials can generate indirect cyber risk. A physical interruption can limit equipment replacement; unreliable components can introduce vulnerabilities; and the lack of industrial capacity can hinder infrastructure upgrade or recovery. Digital security starts before the software and reaches the entire supply chain.

The articulation between mineral, industrial and cybersecurity supports the argument that technological power is the result of combined capabilities. The strategically prepared state needs to know its dependence points, diversify suppliers, develop technical competence, protect intellectual property, maintain stocks or redundancy and adopt responsible AI governance.

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Table 4. Dimensions of technological sovereignty

Capacity	Sovereignty question	Risk of absence
Material	Is there safe access to minerals and components?	Interruption and external dependence
Industrial	Is it possible to process, manufacture and repair?	Low aggregation of value and fragility
Scientific	Is there knowledge to innovate and replace?	Obsolescence and technological dependence
Digital	Can infrastructures and data be operated locally?	Loss of operational autonomy
Cyber	Can systems be audited, protected and recovered?	Exposure to attacks and coercion
Regulatory	Is technology governed legitimately?	Opacity, abuse and loss of trust

Source: author elaboration based on Alves and Conceição (2025), Santana *et al.* (2026) and IEA (2026).

2.6. Geopolitics of rare earth elements

Rare earth geopolitics derives from the interaction between territorial distribution, industrial concentration, international trade, public policies and strategic value of applications. Kalantzakos (2020) shows that competition for critical minerals follows broader geopolitical realignments, while Klare (2012) places the dispute for resources in the context of increasing pressure on essential materials.

China's dominant position is not limited to reserves or mining. It includes separation, refining, metal and alloy production, magnet manufacturing and integration with industrial chains. The IEA (2025, 2026) shows that this concentration creates significant exposure for economies that depend on imports and for high-value downstream sectors.

The United States, the European Union, Japan, Australia and other actors have been adopting diversification policies, agreements, production incentives, stocks and support for recycling. The European Union has strengthened this movement with the Critical Raw Materials Act, which combines goals of extraction, processing, recycling and dependence limits of a single third country.

Africa, Latin America and other regions with mineral potential may acquire greater importance, but they face a risk of repeating low value-added extractive models. The conversion of reserves into development depends on infrastructure, local content trading, qualification, environmental protection, governance and access to processing technologies.

Geopolitics can also use trade as an instrument of pressure. Export restrictions, controls on equipment and licenses can transform industrial concentration into bargaining power. The

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response of importing countries tends to combine diversification, friend-shoring, innovation, recycling and mineral alliances.

However, excessive fragmentation of chains can increase costs and delay environmental and technological objectives. International cooperation remains necessary for environmental standards, transparency, financing and circulation of secondary materials. Mineral safety must balance resilience, sustainability and efficiency.

Geopolitical competition also has an informational dimension. The IICTEC (2026) and Alves and Conceição (2026) demonstrate that public attention and academic visibility can accompany the growing incorporation of material components into AI agenda. Silva (2026), in analyzing the economy of attention, adds that the signs of interaction become data that feed back into algorithmic systems and condition future exposures. This layer does not replace the mineral and industrial basis of power, but helps explain how infrastructure, risks and dependencies gain social and political prominence.

Table 5. Structural positions in rare earth geopolitics

Actor or region	Advantage or potential	Main vulnerability
China	Scale, processing and industrial integration	External pressure for diversification and trade restrictions
United States	Market, innovation and financial capacity	Dependence on intermediate steps
European Union	Regulation, technology and market	Low domestic production and high dependence
Australia	Resources and experience in mining	Need to advance into downstream steps
Africa and Latin America	Geological potential and new projects	Primary export risk and institutional fragility

Source: elaboration of the author based on Kalantzakos (2020), IEA (2025, 2026), USGS (2026) and Demir *et al.* (2026).

2.7. Gaps in the literature

The review shows robust literature on geology, applications, environmental impacts, criticality, trade and geopolitics. However, the fields remain partially fragmented. Environmental studies rarely accompany the resource until it is converted into technological capacity; geopolitical analyses often aggregate different minerals without examining specific bottlenecks; and works on AI tend to treat infrastructure and raw materials as external variables.

The first gap is explanatory: a model that describes the stages and conditions by which geoenvironmental resources become technological sovereignty is missing. Reserve ownership is

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often used as a potential indicator, but it does not explain why some countries extract strategic value and others remain primary suppliers.

The second gap is multidimensional. Criticality indices assess risk of supply, vulnerability or environmental impact, but they do not always integrate sustainability, processing, industry, science, AI infrastructure, cybersecurity and governance in the same comparative framework.

The third gap refers to the link between sustainability and power. Part of the literature treats environmental requirements as costs or restrictions. This article proposes to interpret them as resilience conditions: environmentally degrading chains may suffer social rejection, sanctions, liabilities, delays and loss of competitiveness.

The fourth gap lies in the materiality of the AI. The expansion of intelligent systems is generally discussed in terms of data and algorithms, without sufficient integration with the resources, equipment and industrial chains that sustain its operation.

Finally, there is a methodological gap between conceptual models and measurable instruments. The MCGPT seeks to offer organized causal mechanism, while the IGPE-IA translates its dimensions into a future indicator architecture. The combination aims to build a bridge between theoretical interpretation and empirical comparison.

Table 6. Summary of gaps and contributions of the study

What the literature already explains	Limitation identified	Proposed progress
Criticality and supply risk	Mineral or commercial emphasis	Integration with technological and cyber capacity
Environmental impacts of mining	Separation between environment and geopolitics	Sustainability as a condition of resilience
Chain concentration	Little explanation of the conversion of the resource into power	MCGPT as a transformation mechanism
Infrastructure and expansion of the AI	Mineral materiality poorly integrated	Systemic relationship between AI and industrial chain
Criticality Indexes	Incomplete dimensions for AI	multidimensional IGPE-IA

Source: elaboration of the author (2026).

2.8. Synthesis of the theoretical framework

The reference shows that the importance of rare earth emerges from the interaction between physicochemical properties, supply concentration, processing complexity, high performance applications and relevance for strategic sectors. Its analysis requires an approach

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that goes beyond geology and incorporates environment, industry, technology, institutions and international relations.

The historical evolution of strategic resources shows that power never derived only from physical possession. Coal demanded machinery and transportation; oil required refining and infrastructure; and rare earth elements require sophisticated separation, functional materials, advanced manufacturing and technological integration. The decisive step is conversion capacity.

AI infrastructure reinforces this conclusion. Algorithms depend on equipment, energy, networks, sensors and industrial chains. Digital autonomy is linked to mineral and industrial safety, while cybersecurity depends on the ability to operate, audit, maintain and recover critical systems.

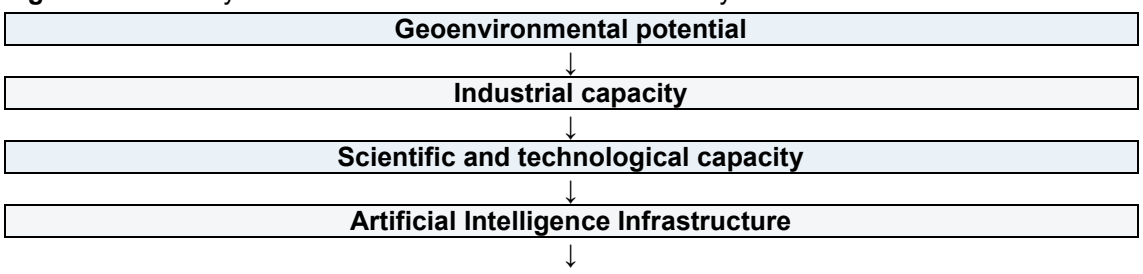
Sustainability goes through all these dimensions. Environmental and social impacts can limit projects and compromise the legitimacy of chains. Recycling, recovery, replacement and efficiency reduce risks, but do not dispense responsible mining and international cooperation.

The literature, however, still does not offer an integrated structure that explicitly represents the sequence by which a geoenvironmental resource can become processing capacity, industry, AI infrastructure, cyber defense, sovereignty and geopolitical influence. This gap supports the proposition of the MCGPT.

The reference also supports the need for IGPE-IA. A country should not be assessed only by reserves or production. It is necessary to observe sustainability, processing, manufacturing, science, energy, digital infrastructure, governance and cybersecurity. These dimensions are developed analytically in Section 4.

In summary, the theoretical argument can be expressed by the following relation: natural resources have strategic potential; industrial capacities convert this potential into technological value; digital and cybernetic capabilities transform technological value into autonomy; and institutions and policies convert autonomy into lasting influence. Section 3 presents the method used to consolidate this structure and substantiate the two proposed instruments.

Figure 2. Summary of the theoretical architecture of the study



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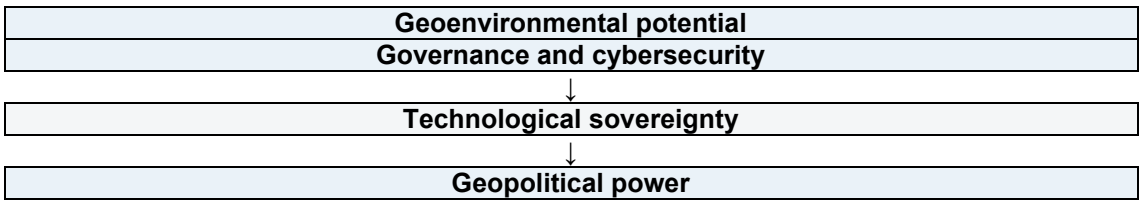

Source: elaboration of the author (2026).

3. METHODOLOGY

3.1. Nature and research approach

This research has a qualitative nature, exploratory character and theoretical-conceptual purpose. The qualitative approach was selected because the objective of the study is not to statistically measure the production or world rare earth reserves, but to interpret the relationships between geoenvironmental resources, production chains, sustainability, Artificial Intelligence, cybersecurity, technological sovereignty and geopolitical power.

Qualitative research allows analyzing complex phenomena from their meanings, contexts, relationships and explanatory mechanisms. This approach is especially appropriate when the problem investigated involves different fields of knowledge and requires an integrated understanding, rather than the isolated verification of quantitative variables. Lim (2024) highlights that qualitative research favors in-depth analysis of complex phenomena, offering contextual and holistic perspectives, although it requires methodological transparency and reflexivity to reduce possible interpretative biases.

In the present study, the qualitative approach was used to construct a theoretical interpretation of the transformation of rare earth into strategic assets. It was based on the understanding that mineral availability does not automatically produce technological sovereignty. Between the existence of the resource and its conversion into geopolitical power are environmental, industrial, scientific, digital, institutional and cybernetic capabilities that needed to be identified and organized analytically.

The research does not intend to test causal relationships through econometric models or assign definitive statistical weights to the proposed dimensions. Its purpose is to develop an explanatory structure based on literature and institutional documents, resulting in the proposition of the Geoenvironmental Conversion Model of Technological Power (MCGPT) and the preliminary dimensions of the Geoenvironmental Index of Strategic Potential for Artificial Intelligence (IGPE-IA).

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3.2. Documentary research

Documentary research was used to examine reports, regulations, government strategies, statistical bases, industrial plans and documents of national and international organizations related to rare earth elements, critical minerals, Artificial Intelligence, economic security and technological sovereignty.

Bowen (2009) defines document analysis as a systematic procedure for examining and interpreting printed or electronic documents, through which data are organized and analyzed to produce empirical understanding and knowledge. Morgan (2022) adds that qualitative documentary research should consider the authenticity, purpose, production context and limitations of the selected documents, avoiding treating them as neutral or independent sources of the interests of the institutions that produced them.

The documentary corpus consisted primarily of:

a) reports from the International Energy Agency, the United States Geological Service, the Organisation for Economic Cooperation and Development and multilateral bodies;
b) documents from the European Union, the United States, China and other countries with specific policies for critical minerals;
c) national strategies for Artificial Intelligence, cybersecurity, mining and industrial policy;
d) public bases on reserves, production, processing, trade and import dependence;
e) regulations on the sustainability, traceability and safety of critical raw material chains.

Documents whose institutional authorship, publication date, purpose and content could be identified were included. Promotional materials without methodological indication, publications without verifiable authorship, duplicate contents and documents without direct relation to the research problem were excluded.

Document analysis was not limited to the reproduction of official numbers and positions. The documents were interpreted critically, considering the geopolitical context in which they were elaborated, the interests of their producers, the priorities declared and the possible differences between political objectives, industrial capacity and effective availability of resources.

3.3. Literature review

The documentary research was complemented by an integrative literature review and oriented to the theoretical construction. Snyder (2019) argues that the literature review can constitute a research methodology when conducted in a transparent and systematically organized way, allowing synthesis of fragmented knowledge, identify gaps and develop conceptual models.

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The bibliographic search covered scientific articles, reviews, books and specialized chapters published preferably between 2000 and July 2026. Previous works were incorporated when they presented indispensable historical or theoretical relevance, especially in the fields of geopolitics of natural resources, international political economy and technological transitions.

Bibliographic recovery was carried out until July 24, 2026 through Consensus, a search mechanism for indexed scientific literature, with complementary verification of authorship, year, journal and DOI in the pages of journals and publishers. For institutional data, primary sources of the IEA, USGS and the European Union were consulted. The searches were conducted in English, Portuguese and Spanish, using combinations of the following terms:

“rare earth elements”, “critical minerals”, “Artificial Intelligence”, “geopolitics”, “technological sovereignty”, “cybersecurity”, “supply chain”, “mineral security”, “environmental sustainability” and “critical raw materials”.

A retrospective audit of the bibliographic matrix identified 51 potentially eligible records. During identification, three duplicate records were removed; the remaining 48 unique records underwent full-text review and eligibility assessment. No additional records were excluded at that stage, and the final corpus therefore comprised 48 scientific and institutional sources. This numerical flow refers to the records effectively entered in the working matrix and should not be interpreted as an estimate of the total results returned by the search engines.

Source quality and relevance were assessed using four criteria: (a) authority and traceability of authorship; (b) peer review or the official status of the issuing institution; (c) methodological transparency and data verifiability; and (d) a direct relationship with at least one MCGPT or IGPE-IA dimension. Earlier seminal works were retained only when indispensable to the historical or theoretical foundation. Promotional sources, items without verifiable authorship or an identifiable method, and materials merely tangential to the research problem were considered ineligible.

Throughout the article, the term “index” denotes a conceptual proposal: the IGPE-IA has not yet undergone empirical validation and currently has no weights, scale, composite score, or ranking capability.

Studies with direct relation to at least one of the dimensions of the study were included: mineral availability; extraction and sustainability; processing and refining; advanced materials industry; AI infrastructure; cybersecurity; technological sovereignty; or geopolitical influence. Peer-reviewed studies, methodologically transparent documents and publications of recognized scientific or institutional relevance were prioritized.

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The review was not conducted as a meta-analysis, as the corpus gathered heterogeneous evidence from environmental, geological, economic, technological and geopolitical studies. Its purpose was to construct an interdisciplinary synthesis capable of identifying relationships, convergences, divergences and gaps between fields that often analyze the phenomenon in a fragmented way.

3.4. Thematic analysis

The selected materials were submitted to thematic analysis, understood as a method of identification, organization and interpretation of patterns of meaning present in qualitative data. Clarke and Braun (2017) explain that thematic analysis offers flexibility to work with different theoretical perspectives, provided the researcher expresses the coding criteria and recognizes its active role in the construction of the themes.

The analysis was developed in five stages:

1. full reading and familiarization with articles and documents;
2. identification and coding of units of significance related to the research problem;
3. grouping codes into preliminary thematic categories;
4. review of categories, with comparison between scientific and institutional sources;
5. definition of the central themes and relations between them.

The initial categories were guided by the theoretical framework, but remained open to the incorporation of emerging dimensions. Among the preliminary categories were: geoenvironmental availability; extraction sustainability; processing capacity; industrial value aggregation; technological infrastructure; Artificial Intelligence; cybersecurity; technological sovereignty; external dependence; and geopolitical power.

Coding was not intended only to account for the frequency of terms. A certain category could be considered theoretically relevant even when it appeared in a small number of sources, provided it contributed to explain the mechanisms for transforming geoenvironmental resources into strategic capacity.

3.5. Interpretive synthesis

After the thematic analysis, an interpretative synthesis was performed to articulate the documentary and bibliographic results. Dixon-Woods (2011) notes that qualitative synthesis based on conceptual structures can use an initial model as a coding reference, modifying it as new factors and relationships are identified in the corpus analyzed.

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In this study, the synthesis occurred through comparison between the categories, identification of causal or conditional relationships and organization of the stages that connect natural resources, productive capacities and geopolitical influence. The procedure sought not only to summarize what each author said, but to produce an integrative interpretation that explained why the existence of mineral reserves generates different strategic results between countries.

The interpretive synthesis supported the construction of the MCGPT. Each component of the model presents correspondence with evidence identified in the literature or in the documents analyzed. The same procedure guided the formulation of the preliminary dimensions of the IGPE-IA, without this implying, at this stage, statistical validation or definitive weight assignment.

To increase the reliability of the study, the following procedures were adopted: registration of search strategies; explicit inclusion and exclusion criteria; comparison between different types of sources; identification of contradictory information; traceability between categories and evidence; and distinction between results extracted from the sources and interpretations proposed by the author.

Since the research used exclusively public documents and scientific publications, there was no interaction with human participants or collection of personal data. Still, the principles of scientific integrity, fidelity to sources, methodological transparency and respect for authorship were observed.

3.6. Declaration on the use of Artificial Intelligence

Generative Artificial Intelligence tools were used exclusively to support language editing, translation, and formal review. The authors fully verified the content, citations, and references, accept responsibility for the final version, and did not delegate authorship, scientific interpretation, or evidence assessment decisions to AI. This disclosure follows international principles of transparency, human oversight, accountability, and editorial integrity (Miao and Holmes, 2023; Zielinski *et al.*, 2023; International Committee of Medical Journal Editors, 2026).

4. RESULTS AND DISCUSSION

4.1. Interpretive synthesis of the evidence

The thematic analysis produced a central result: a country's strategic position in the rare earth economy cannot be inferred from an isolated variable, such as reserve, mineral production or number of patents. Evidence converges to an architecture of complementary capabilities, in which geopolitical value emerges from the articulation between geoenvironmental base,

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sustainable extraction, processing, advanced manufacturing, science, Artificial Intelligence infrastructure, governance and resilience. Mineral availability is a condition of possibility; technoindustrial conversion determines how much of this potential becomes autonomy and power.

The latest data make this difference between allocation and conversion visible. USGS estimated world rare earth production at 390,000 tonnes of rare earth oxide (REO) in 2025, of which 270,000 tonnes were produced by China, approximately 69.2% of the total. The same survey recorded 44 million tons of Chinese reserves and 21 million tons in Brazil; however, Brazilian production was estimated at only 2,000 tons. The contrast does not in itself demonstrate causality between industrialization and power, but constitutes descriptive evidence that an expressive geological base can coexist with low productive conversion (USGS, 2026).

The asymmetry increases as the chain advances. For the four rare earth elements used in magnets (neodymium, praseodymium, dysprosium and terbium), the IEA calculated that China accounted in 2024 for 60% of mining, 91% of refining and 94% of production of permanent sintered magnets. The percentage progression in the downstream direction demonstrates that the main center of strategic gravity is in the stages of separation, metallization, alloy and magnet manufacturing, and not only in extraction (IEA, 2026). This pattern is consistent with Zhang *et al.* (2022), whose network analysis and panel regression showed that international competition varies according to the stage of the chain and that the position in downstream activities is decisive for the elevation of status in global value chains.

Demand reinforces the structural character of the problem. According to the IEA (2026), the demand for the four magnetic elements has doubled since 2015 and, under current policies, is expected to grow by about one third by 2030. NdFeB magnets support motors, actuators, robotics, energy systems and AI data centers equipment; therefore, the dependence is not due to the algorithm containing rare earth elements, but to the electromechanical and energy infrastructure that supports it depending on functional materials. This interpretation is consistent with Stacciarini and Gonçalves (2025) and Valdivia (2024), who treat AI as a material, energy, territorial and labor chain, and not as an exclusively immaterial artifact.

Concentration also has measurable economic effects. Fan, Omura and Roca (2023) found statistically significant relations between geopolitical risk, prices and Japanese imports of rare earth. In a scenario of full application of export controls announced in 2025, the IEA (2026) estimated that US$6.5 trillion of annual downstream production outside China would be exposed, with direct potential losses exceeding US$1.5 trillion in both the United States and Europe. It is a

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scenario of stress, not prediction, but its magnitude shows the difference between the relatively limited value of the mineral market and the economic value of the systems that depend on it.

The announced diversification remains unbalanced. For 2035, existing and announced capacities outside the dominant producer would cover approximately 50% of China's external demand in mining, 25% in refining and less than 20% in magnets. Full coverage would require, in addition to the projects already announced, multiply by about two the mining capacity, by four the refining capacity and by six the magnets, with estimated need of US$ 60 billion investment in the decade (IEA, 2026). Therefore, opening mines without installing separation, metalization and manufacturing can diversify the origin of the ore without eliminating technological dependence.

Sustainability has emerged as an internal condition of resilience. Han *et al.* (2025) systematize risks of soil acidification, water contamination, heavy metals and radioactive materials associated with certain deposits and processes. Lee and Wen (2018) estimated net environmental costs of Chinese production and demonstrated that monitoring, legal production and cleaner technologies significantly alter the environmental and economic balance. The IEA (2026) adds that recycling can reduce the need for primary rare earth supply to magnets by up to 35% in 2050. Thus, licensing, traceability, waste management and circularity are not only normative requirements: they influence operational continuity, financing, social acceptance and shock response capacity.

Table 7 organizes the main documentary evidence that gave rise to the proposed model and framework. The final column does not literally reproduce the sources; it explains the theoretical inference made by the author from triangulation. This separation is necessary because the data support the plausibility of the mechanisms, but do not statistically validate the MCGPT or IGPE-IA.

Table 7. Traceability matrix between evidence and analytical inferences

Evidence verified	Documentary result	Model Inference
USGS (2026)	World production of 390 thousand t REO in 2025; China: 270 thousand t. Reserves: China 44 million t; Brazil 21 million t, with Brazilian production of 2,000 t.	Significant reserves do not ensure productive conversion capacity.
IEA (2026)	China: 60% of mining, 91% of refining and 94% of sintered magnets for magnetic rare earth elements in 2024.	Control increases in downstream steps; processing and manufacturing are strategic bottlenecks.

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Evidence verified	Documentary result	Model Inference
IEA (2026)	Demand of magnetic elements doubled since 2015 and is expected to grow by about one third by 2030.	Technological expansion increases the value of material chains associated with AI, automation and energy.
Zhang *et al.* (2022)	Competition and position in the global chain vary by stage, with strong downstream intensity.	Aggregation of value and industrial complexity better explain the advantage than gross export.
Fan, Omura and Roca (2023)	Geopolitical risk presents significant relations with Japanese rare earth prices and imports.	Concentrated dependence can convert economic interdependence into vulnerability and influence.
Han *et al.* (2025); Lee and Wen (2018)	Extraction and processing produce relevant environmental costs; practices and supervision alter these costs.	Sustainability is a mechanism of continuity and resilience, not a variable external to power.
Stacciarini and Gonçalves (2025); Valdivia (2024)	AI depends on data, energy, equipment, minerals, water and industrial chains.	AI sovereignty has a material and territorial dimension as well as software, models and data.
Kumar and Mallipeddi (2022)	Digitization and integration of chains increase cyber risks and require interorganizational management.	Technological capacity only becomes sovereignty when systems and suppliers are protected and recoverable.

Source: author elaboration based on the sources indicated. The USGS values refer to rare earth oxide equivalents (REO); the IEA percentages for the mine-to-magnet chain cover Nd, Pr, Dy and Tb.

4.2. Geoenvironmental Conversion Model of Technological Power (MCGPT)

The Geoenvironmental Conversion Model of Technological Power (MCGPT) is a theoretical-explanatory structure intended to represent how a potentially strategic natural resource can be transformed into technological capacity and geopolitical influence. The model answers the question “by what mechanism can geoenvironmental allocation become power?”, avoiding mineral determinism. Its unit of analysis can be a country, a region or a productive alliance, provided the analytical boundaries are explained. Thus, the model is graphically represented in Figure 3.

Figure 3. Geoenvironmental Conversion Model of Technological Power (MCGPT)
Source: Own elaboration (2026), based on the synthesis of the literature analyzed

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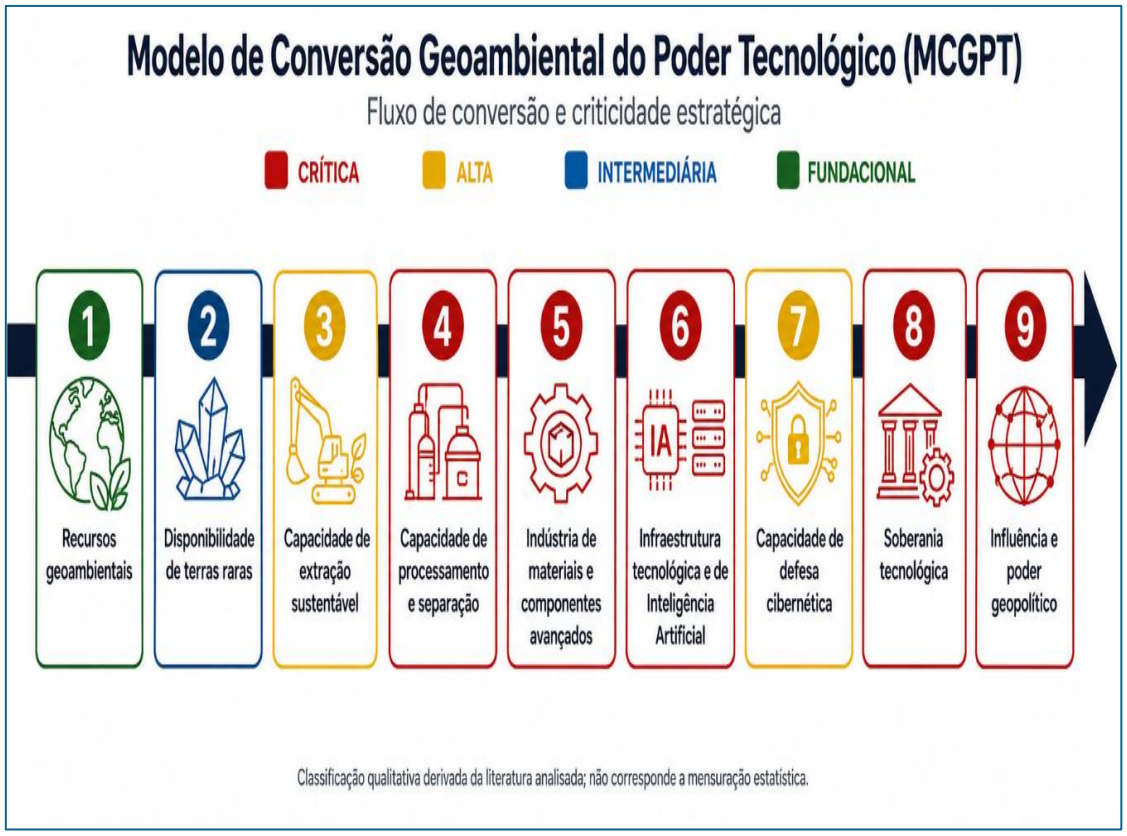

The chromatic classification of Figure 3 is initially based on the theory of mineral criticality, according to which the strategic importance of a resource arises not only from its geological existence, but from the combination of supply risk, environmental impacts and vulnerability to supply restrictions (Nassar, Du and Graedel, 2015). For this reason, the geoenvironmental resources — stage 1 — received the green color, because they represent a foundational but still potential condition: having reserves does not mean controlling their exploitation or obtaining political or economic power. The availability of rare earth elements — stage 2 — has been classified in blue, because the presence of economically accessible deposits increases the strategic potential, but remains insufficient without complementary productive capacities. Haque *et al.* (2014) show that although there are numerous deposits identified, only a small portion is effectively transformed into operational mines. The sustainable extraction capacity — step 3 — received yellow color, as water and energy consumption, waste generation, radioactivity, licensing and social acceptance condition the continuity of production. It is therefore a highly

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relevant capacity, but still located in the primary segment of the chain and prior to the stages of greater value aggregation.

The processing and separation capacity — step 4, the advanced materials and components industry — step 5 and the technology and Artificial Intelligence infrastructure — step 6 received the red color for constituting the main bottlenecks for converting the mineral resource into technological capacity. This interpretation is supported by the theory of global value chains of Gereffi, Humphrey and Sturgeon (2005), according to which the complexity of transactions, the possibility of coding knowledge and the capabilities of suppliers produce different structures of coordination and asymmetries of power. In the case of rare earth elements, separating chemically similar elements, producing functional materials and manufacturing magnets, sensors, semiconductors and components requires tacit knowledge, industrial scale and specialized infrastructure. Kalantzakos (2020) shows that the digital-energy transition and the Fourth Industrial Revolution have transformed continuous access to critical minerals into an object of geopolitical competition. Liu *et al.* (2025) add evidence that the intermediate and final segments of the chain have strong sensitivity to cooperation and conflict relations between countries. Thus, steps 4, 5 and 6 are critical because they determine who controls value aggregation and manages to convert raw material into computing, automation, digital infrastructure and defense capacity.

The cyber defense capacity — step 7 — has been classified as yellow because it is of high importance to protect, audit and recover critical infrastructure, although it plays a predominantly protective role: it alone does not replace previous industrial, scientific and computational capabilities. Calderaro and Blumfelde (2022) show that merely regulatory sovereignty is insufficient when the country has no advanced AI industry and a coherent defense strategy. The technological sovereignty — step 8 — received the red color because it represents the ability to control technologies, infrastructures, data and strategic decisions, in accordance with the conception of digital sovereignty developed by Floridi (2020). Finally, the influence and geopolitical power — stage 9 — were also represented in red, as they constituted the culmination of the model: the ability to condition markets, negotiate from less dependent positions and exert influence on international chains. The color of step 9 indicates its centrality as a strategic result, not an independent variable. Thus, the chromatic scale is a theoretical-qualitative classification derived from the literature, not corresponding to statistically validated weights or measurements.

The notion of conversion is central. Each passage simultaneously changes the material form, economic value, intensity of knowledge and exposure to risk. Concentrated ore is not equivalent to separate oxide; separate oxide is not equivalent to metal or alloy; and a magnet is

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not equivalent to a technological system capable of operating safely. As the resource advances, the advantage depends less on gross physical volume and more on tacit knowledge, specialized equipment, quality, intellectual property, scale, energy, coordination and market access.

The MCGPT has three blocks. The first is the geoenvironmental base, composed of the existence and knowledge of resources, their distribution by element, mineralogical characteristics and territorial conditions of access. The second is the technoindustrial conversion, which covers sustainable extraction, processing, separation, refining, metalization, alloys, magnets, components and integration into AI infrastructure. The third brings together the strategic results: resilience, technological sovereignty and ability to influence. Science, energy, logistics, financing, institutions, social and environmental governance, cybersecurity and data protection cross the entire chain.

Figure 4. Synthetic MCGPT Architecture

GEOENVIRONMENTAL BASIS	TECHNOINDUSTRIAL CONVERSION	STRATEGIC RESULTS
Reserves and resources per item Quality of deposit Material and logistical access	**Sustainable extraction → separation and refining → metals, alloys and magnets → AI equipment and infrastructure**	**Strategic resilience Technological sovereignty Geopolitical influence**
TRANSVERSAL CAPACITIES: science and innovation		
FEEDBACK AND CIRCULARITY: learning, revenue, recycling, replacement, industrial policy and alliances reconfigure the previous steps; any bottleneck can limit conversion.		

Source: elaboration of the author (2026), from the documental and bibliographic synthesis.

4.2.1. Components and conversion mechanisms

The first component is the geoenvironmental potential. It includes reserves and resources, but is not limited to aggregate volume. Nassar, Du and Graedel (2015) demonstrate that risk of supply, environmental implications and vulnerability to restriction vary among the elements. Kosajan, Wen and Wang (2025) reinforce that Pr, Nd and Dy have different criticality profiles and that aggregated decisions can produce incorrect diagnoses. Therefore, the MCGPT

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requires minimal breakdown of the relevant elements for the analyzed application and information on content, mineralogy, coproduction and maturity of geological knowledge.

The second component is sustainable and socially legitimate extraction. The resource only enters the chain when there is technical feasibility, licensing, water, energy, infrastructure, waste management and social acceptance. Sustainability acts as a capacity variable: uncontrolled impacts increase liabilities, delays, opposition, financing costs, and the likelihood of interruption. The model therefore rejects the equivalence between nominal capacity and resilient capacity.

The third component is processing, understood as beneficiation, chemical separation, purification and refining. The separation is technologically intensive because elements of similar chemical behavior need to achieve high specifications. The 91% concentration of magnetic rare earth refining in China in 2024 shows that this stage is a power node. The mere existence of concentrate does not guarantee access to individualized oxides nor reduces dependence on equipment, reagents or external knowledge (IEA, 2026).

The fourth component is industrial value aggregation. It includes metallization, powder and alloy production, magnet manufacturing, sensors, motors and components. The finding of Zhang *et al.* (2022) on downstream competition supports the proposition that manufacturing density changes the position of a country in the chain. In addition to the monetary value, this stage generates learning, technical standards, supply relations and repair capacity, which are difficult to replace in the short term.

The fifth component is scientific-technological capacity. Laboratories, qualified personnel, patents, pilot plants, metrology, research in separation, replacement and recycling allow reducing costs, adapting ores and responding to scarcity. This capacity is not an isolated stage, but a multiplier that acts on the entire chain. The evidence of Zhao, Cheng and Xu (2026), according to which the technological capacity of alternative suppliers weighs more than the geopolitical proximity in the reconfiguration of the chain, reinforces this function.

The sixth component is the material infrastructure of the AI. It covers data centers, networks, storage, energy, cooling, robotics, sensors, power systems and maintenance. The IEA (2026) links high-performance magnets to data centers, automation and digital technologies. The MCGPT does not state that the entire AI system directly requires large mass of rare earth elements; it states that AI scale is supported by electromechanical and energy ecosystems whose material dependencies should be tracked.

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The seventh component is governance and security. It includes mineral and industrial policy, regulatory coordination, investment assessment, traceability, contracts, strategic reserves, responsible AI governance, cybersecurity and data protection. Inclusion arises from a logical condition: infrastructure that cannot be audited, protected or recovered does not produce reliable autonomy. Kumar and Mallipeddi (2022) show that digital integration of operations creates cyber risks that cross organizational boundaries, making suppliers and third parties part of the risk surface.

The eighth component is the geopolitical result. Influence does not mean domination, but ability to maintain options, reduce coercion, participate in patterns, negotiate alliances and sustain critical sectors during shocks. The MCGPT distinguishes potential power from power exercised: installed capabilities increase strategic options, but their conversion into influence depends on state strategy, coordination between actors and international context.

Table 8. MCGPT components and mechanism hypotheses

Component	Function in the process	Typical failure or bottleneck	Expected result
1. Geoenvironmental potential	Defines the material base and its quality per element.	Frail geological data; resource without viability.	Material option informed.
2. Sustainable extraction	Transforms resource into licensed and continuous offer.	Environmental liabilities; social conflict; lack of water/energy.	Resilient production.
3. Separation and refining	It produces individualized and high purity oxides.	Technology and equipment dependencies.	Safety of processed materials.
4. Downstream industry	It converts oxides into metals, alloys, magnets and components.	Primary export; lack of scale and buyers.	Value added and learning.
5. Science and innovation	Improve processes, replacement, recycling and adaptation.	Lack of skills and pilot plants.	Dynamic response capability.
6. AI infrastructure	It integrates components, energy, computing and automation.	External systems dependence and maintenance.	Operational technological capability.
7. Governance and security	Coordinates risks, data, suppliers and continuity.	Institutional fragmentation; cyber vulnerabilities.	Reliable and legitimate autonomy.

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Component	Function in the process	Typical failure or bottleneck	Expected result
8. Geopolitical result	It converts autonomy into options, alliances and influence.	No external strategy or coherence.	Negotiation power and less exposure.

Source: elaboration of the author (2026). The relationships are theoretical propositions based, not yet causal estimates.

4.2.2. Analytical properties of the MCGPT

The model has five properties. The first is nonlinearity: shocks, innovation, recycling and policies can reconfigure the chain, and the flow does not occur once. The second is complementarity: resources, industry and knowledge produce higher results when combined. The third is the logic of the limiting link: large upstream allocation does not automatically compensate for lack of refining, magnets or cyber-resilience. The fourth is cumulativeness: scale, learning and supplier networks can reinforce existing advantages. The fifth is multiscale: no economy needs to internalize all stages, since alliances and contracts produce reliable, diversified and governed access.

For formal purposes, the potential strategic result can be represented only in a heuristic way as P* = f(GE, ES, PR, VA, CT, II, SG, RG), in which GE corresponds to the geoenvironmental base; ES, sustainable extraction; PR, processing and refining; VA, value aggregation; CT, scientific-technological capacity; II, AI infrastructure; SG, governance and security; and RG, geopolitical resilience. The expression does not constitute an estimated equation, does not fix functional form and does not authorize calculation. Its function is to make explicit the dimensions and allow future research to test complementarity, thresholds, mediation and bottleneck effects.

4.3. Discussion of the MCGPT in light of the literature

The MCGPT brings together three traditions that normally operate separately. Criticality literature models risk of supply, vulnerability and environmental implications; global value chain literature examines aggregation, competition and upgrading; and technological sovereignty literature discusses decision-making autonomy, infrastructure and security. The contribution of the model is to organize these traditions as a conversion mechanism, not just as a list of factors.

Regarding criticality models, the MCGPT maintains the multidimensionality of Nassar, Du and Graedel (2015), but shifts the focus of the material to the sociotechnical capacity that transforms it. The risk of supply remains necessary, but insufficient to explain why countries with similar availability reach different positions. Gemechu *et al.* (2016) demonstrate that commercial

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exposure and geopolitical concentration can be incorporated into risk indicators; the MCGPT adds the question about which capacities allow reducing this exposure.

Regarding value chains, the model converges with Zhang *et al.* (2022) when recognizing the heterogeneity of the stages. His theoretical advance is to treat the upstream-downstream passage as both material and political conversion. Processing and manufacturing not only capture income: they generate tacit knowledge, standards, maintenance capacity and power of interruption. The concentration of 94% of sintered magnets in a single country provides documentary evidence compatible with this proposition (IEA, 2026).

Regarding sustainability, MCGPT differs from approaches that represent it only as a cost. The results of Lee and Wen (2018), Han *et al.* (2025) and IEA (2026) justify treating it as an attribute of productive capacity. Chains that outsource contamination may seem competitive in the short term, but accumulate liabilities and instability. On the other hand, more demanding standards raise initial costs, which requires policy and financing instruments to prevent responsible diversification from being made impossible by competition based on externalization.

In relation to AI, the MCGPT adopts an infrastructural interpretation. Stacciarini and Gonçalves (2025) and Valdivia (2024) show that data centers and electronic chains depend on minerals, water, energy and territory. The model specifies the place of rare earth elements in this materiality: especially in magnets, motors, actuators, sensors and auxiliary systems. This precision avoids two extremes — presenting AI as immaterial or assigning rare earth elements an exclusive role that belongs to a wider set of critical minerals.

Finally, the MCGPT interprets sovereignty as governed resilience, not as self-sufficiency. The restructuring analysed by Zhao, Cheng and Xu (2026) shows that reducing dependency can increase costs and that alternative suppliers need technological capacity. Diversification should therefore be assessed by the existence of substitute routes, interoperability, quality and recovery time, and not only by the number of supplier countries.

4.4. Proposal of the IGPE-IA as an analytical framework

The Geoenvironmental Index of Strategic Potential for Artificial Intelligence (IGPE-IA), whose graphic representation is presented in Figure 5, is proposed as an analytical framework to evaluate, in future research, the potential of a country, region or alliance to convert geoenvironmental assets into AI-related strategic capacity. In this article, the term “index” designates a conceptual architecture of candidate dimensions and indicators. There is no scoring, normalization, weighting, aggregation or classification of countries.

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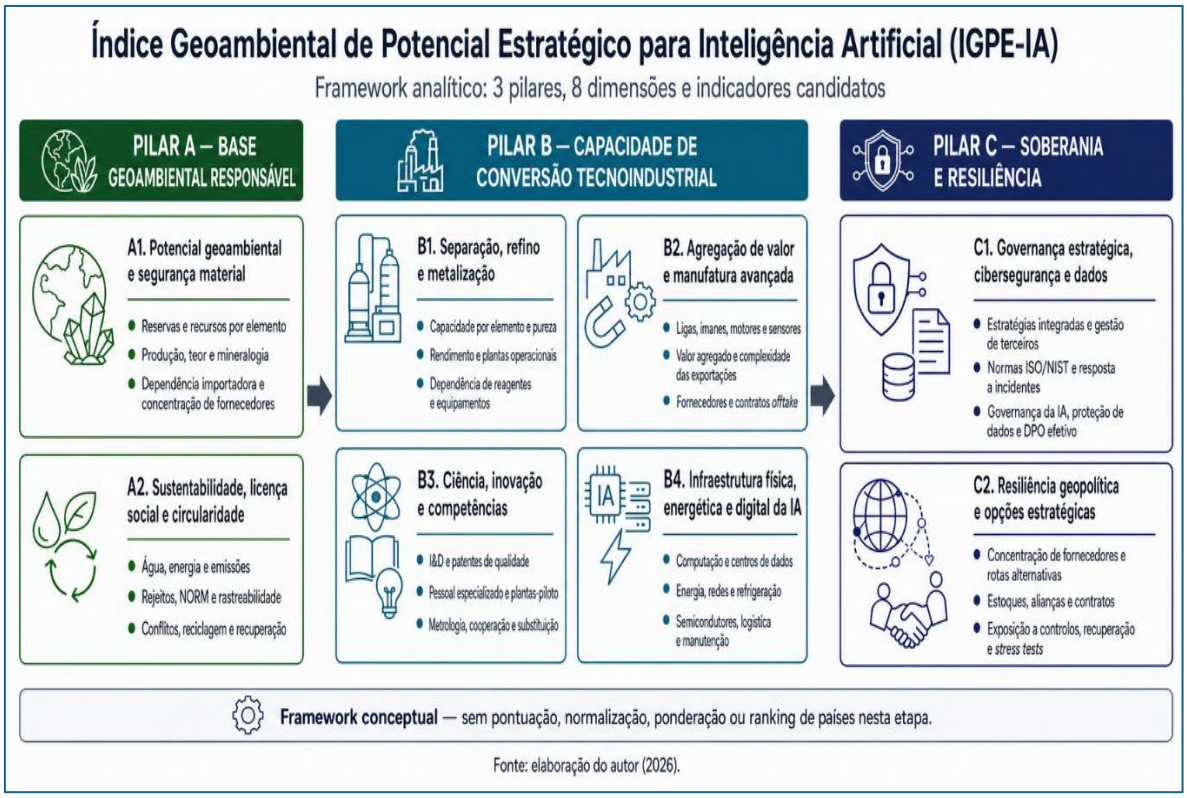
Figure 5. Conceptual architecture of the Geoenvironmental Index of Strategic Potential for Artificial Intelligence (IGPE-IA)



Source: elaboration of the author (2026).

Figure 5 should be read from left to right, following the passage from the geoenvironmental base to the technoindustrial conversion capacity and finally to sovereignty and resilience. The IGPE-IA translates the explanatory mechanism of the MCGPT into a diagnostic architecture consisting of three pillars and eight dimensions. Its foundation combines the multidimensional theory of mineral criticality, which relates risk of supply, environmental implications and vulnerability to restrictions (Nassar, Du and Graedel, 2015), the theory of global value chains, which explains how productive capacities and asymmetries of coordination determine value appropriation (Gereffi, Humphrey and Sturgeon, 2005), and the approach to digital sovereignty, centered on legitimate control of technologies, data and infrastructures (Floridi, 2020). These approaches, however, remain fragmented: none of them, alone, allows assessing how geoenvironmental assets can be converted into AI infrastructure, cybersecurity and geopolitical influence. In the document corpus analyzed, this is the specific integrating gap filled by the IGPE-IA.

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The Pillar A — Responsible geoenvironmental base comprises two dimensions. The A1 dimension — geoenvironmental potential and material security considers reserves and resources disaggregated by element, effective production, content, mineralogy, importer dependence and supplier concentration. This structure stems from the theory of mineral criticality, according to which geological abundance does not automatically equate to security of supply, because criticality also depends on substitutability, production concentration and geopolitical exposure (Nassar, Du and Graedel, 2015; Gemechu *et al.*, 2016). Dimension A2 — Sustainability, social licence and circularity adds water and energy consumption, emissions, waste, radioactive materials of natural occurrence, traceability, social conflicts, recycling and recovery. Haque *et al.* (2014) and Edahbi, Plante and Benzaazoua (2019) show that environmental impacts can compromise the continuity of enterprises, while Wang *et al.* (2024) show the potential of the circular economy to reduce supply imbalances. The original advance of the IGPE-IA consists of gathering mineral allocation, external exposure, environmental sustainability, social legitimacy and circularity on a single analytical basis, preventing large reserves from being interpreted, in isolation, as a strategic advantage.

Pillar B — Technological industrial conversion capacity represents the value aggregation core. Dimension B1 — Separation, refining and metallization observes capacity by element and degree of purity, yield, operational plants and dependence on reagents and equipment, recognizing that processing is one of the main bottlenecks of the chain (IEA, 2025, 2026; Demir *et al.*, 2026). The B2 dimension — Advanced value aggregation and manufacturing examines alloys, magnets, motors, sensors, export complexity and industrial contracts, in line with the theory of global value chains of Gereffi, Humphrey and Sturgeon (2005). Dimension B3 — Science, innovation and skills incorporates research and development, patents, specialized personnel, pilot plants, metrology and university-industry cooperation, as the ability to learn, adapt and replace technologies conditions the domain of the most complex stages. The B4 dimension — AI's physical, energy and digital infrastructure includes computing, data centres, energy, networks, refrigeration, semiconductors, logistics and maintenance, recognizing the materiality of AI highlighted by Calderaro and Blumfelde (2022). The gap filled by IGPE-IA is to jointly analyze mineral processing, manufacturing, science and physical infrastructure of AI, dimensions normally studied in separate fields.

Pillar C — Sovereignty and resilience checks whether previous capabilities can be governed, protected, and maintained in the face of shocks. The C1 dimension — Strategic governance, cybersecurity and data includes institutional coordination, third-party management,

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ISO and NIST standards, incident response, AI governance, data protection and effective performance of the controller/DPO. This dimension is supported by Floridi's conception of digital sovereignty (2020), by Calderaro and Blumfelde's studies (2022) on the insufficiency of an exclusively regulatory sovereignty, by AI applications in compliance audits discussed by Alves and Conceição (2025) and by Lima and Alves's governance function (2021). The C2 dimension — Geopolitical resilience and strategic options examines the concentration of suppliers, alternative routes, stocks, alliances, contracts, exposure to export controls, recovery time and stress tests, relying on studies by Kalantzakos (2020) and Adekoya, Oliyide and Oduyemi (2023) on mineral dependence and geopolitical risk. The differential of IGPE-IA is to integrate mineral security, industrial capacity, digital governance, data protection, cybersecurity and geopolitical resilience into the same framework. At this stage, however, it organizes constructs and candidate indicators, does not produce country scores, weightings or rankings.

The distinction between the two artifacts is functional. The MCGPT is explanatory: it represents the mechanism and its bottlenecks. The IGPE-IA is a diagnosis: it translates the components of the model into questions and observable variables. One investigates “how conversion occurs”; the other prepares “what will need to be observed to evaluate the conversion potential”. This relationship prevents the framework from being confused with ranking and preserves the coherence between theory and future measurement.

Epistemological delimitation: IGPE-IA does not measure the current power of countries in this investigation. It organizes constructs, candidate indicators and potential sources. Any future score will depend on content validity, data availability and comparability, weighting method, sensitivity tests, uncertainty analysis and external validation.

Table 9. Differences and complementarities between MCGPT and IGPE-IA

Criteria	MCGPT	IGPE-IA
Nature	Explanatory conceptual model.	Analytical framework oriented to future operationalization.
Question	How do resources become capacity and influence?	What dimensions and evidences allow us to evaluate the potential for conversion?
Structure	Steps, mechanisms, enablers and bottlenecks.	Pillars, constructs, candidate indicators and sources.
Result in this article	Grounded theoretical proposition.	Conceptual architecture without scoring or ranking.

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Criteria	MCGPT	IGPE-IA
Future validation	Case studies, process tracing and relationship testing.	Delphi, factor analysis, weighting, sensitivity and comparative validation.

Source: elaboration of the author (2026).

4.4.1. Candidate pillars, dimensions, and indicators

As previously presented, the IGPE-IA is organized into three pillars and eight dimensions, but in a more detailed way it is worth highlighting the conceptual architecture of the model, in which Pillar A, responsible geoenvironmental base, examines the quality of the allocation and the environmental conditions of its mobilization. Pilar B, Technology-industrial conversion capacity, observes processing, manufacturing, science and AI infrastructure. Pilar C, Sovereignty and resilience, assesses governance, security, diversification and preparation for shocks. The architecture avoids rewarding reserves that cannot be transformed in a sustainable way and avoids classifying as sovereign a materially fragile digital infrastructure.

Indicators should be broken down whenever technically possible. Total rare earth reserves can hide the absence of Nd, Pr, Dy or Tb; refining capacity can hide low purity or equipment dependency; number of data centers can hide energy fragility; and the existence of legislation can hide low implementation capacity. The orientation is to combine measures of stock, flow, quality, concentration, institutional capacity and performance.

Table 10. Conceptual architecture of IGPE-IA

Pillar and dimension	Appraisal construct	Candidate indicators	Potential sources
A1. Geoenvironmental potential and material safety	Usable geological base and access to relevant elements.	Reserves/resources per element; production; content and mineralogy; importer dependence; concentration of suppliers; maturity of deposits.	USGS; geological services; UN Comtrade; national statistics.
A2. Sustainability, social licence and circularity	Ability to produce with environmental and social continuity.	Water/energy intensity; emissions; waste management and NORM; traceability; conflicts; recycled content; recovery rate.	LCA; environmental reports; EITI; regulatory agencies; IEA.

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Pillar and dimension	Appraisal construct	Candidate indicators	Potential sources
B1. Separation, refining and metallization	Ability to produce individualized materials in industrial specification.	Annual capacity per element/purity; yield; operational plants; reagent/equipment dependency; expansion time.	IEA; industrial associations; ministries; audited business data.
B2. Value aggregation and advanced manufacturing	Conversion into alloys, magnets, components and systems.	Magnet capacity; motor/sensor production; domestic value added; export complexity; suppliers and off-take contracts.	UNIDO; OECD TiVA; Comtrade; IEA; industrial statistics.
B3. Science, innovation and skills	Ability to learn, adapt, replace and recycle.	R&D; quality patents; specialized staff; pilot plants; metrology; university-industry collaboration; installed research capacity.	WIPO/PATSTAT; UNESCO; OECD; scientific bases; innovation agencies.
B4. AI physical, energy and digital infrastructure	Ability to operate AI and automation in a stable way.	Computing and data centers; reliable energy; network and cooling; semiconductor/equipment; logistics; maintenance; carbon intensity.	IEA; ITU; Uptime Institute; energy regulators; digital statistics.
C1. Strategic governance, cybersecurity and data	Ability to coordinate, audit, protect and legitimize systems.	Integrated strategies; third-party management; ISO/NIST standards; incident maturity; AI governance; data protection; effective controller/DPO.	Laws and strategies; cybersecurity and data protection authorities; audits; maturity reports.
C2. Geopolitical resilience and strategic options	Ability to maintain operations during shocks and coercion.	HHI of suppliers; alternative routes; days of stock; alliances/contracts; exposure to controls; recovery time; stress tests.	IEA; Comtrade; CRMA; public inventories; international agreements.

Source: elaboration of the author (2026). The list is preliminary and does not imply uniform availability or equivalence between sources.

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4.4.2. Rules for future operationalization

The future transformation of the framework into a quantitative instrument should begin with content validation. A multidisciplinary panel — geology, mineral engineering, environment, industrial economy, AI, cybersecurity, data protection and international relations — should assess relevance, clarity and non-redundancy of indicators. Delphi techniques can support consensus; however, panel composition and conflicts of interest need to be published.

The second stage should define unit, period and level of breakdown. Countries are not perfectly comparable when reserves have different degrees of confidence, nominal capacity differs from effective production or magnet data are protected by commercial secrecy. It is recommended to distinguish installed capacity, real production, quality and external dependence, as well as to use time series to avoid single year portraits.

The third stage will be standardization. Benefit and risk indicators require opposite directions; asymmetric distributions may require logarithmic transformation; and extreme values should not dominate results. Min-max normalization is simple, but sensitive to extremes; z scores presuppose statistical comparability; distance reference methods require justifiable benchmarks. The method chosen should be tested in alternative scenarios.

The fourth stage will be weighting. Equal weights are transparent, but they imply judgment of equivalence. AHP or Delphi make judgment explicit, but they can reproduce biases from experts. Statistical or entropy methods depend on the structure of the data and do not necessarily represent normative importance. The recommendation is to publish results with more than one scheme and report position stability instead of treating a weight as objective truth.

The fifth stage will be aggregation. A compensatory sum would allow excellent geological allocation to conceal critical cybersecurity or refining deficiency, contrary to the MCGPT bottleneck logic. Therefore, future research should compare additive aggregation with geometric means, non-compensatory rules or minimum thresholds per pillar. The choice should reflect the theoretical hypothesis and be accompanied by analysis of sensitivity and uncertainty.

The sixth stage will be external validation. The operational index should be confronted with observable results such as duration of interruptions, ability to replace suppliers, downstream participation, export complexity, recovery time and continuity of critical infrastructure. Longitudinal studies, case studies and process tracing will be necessary before any causal interpretation.

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Table 11. Recommended protocol for future validation of IGPE-IA

Step	Methodological decision	Minimum quality test
1. Content Validity	Review dimensions and indicators with multidisciplinary panel.	Content validity index; justification for inclusions and exclusions.
2. Database	Set unit, period, breakdown and rules for missing data.	Data dictionary; provenance; comparability and temporal coverage.
3. Standardization	Convert scales without deleting direction and uncertainty.	Compare methods; examine extremes and distributions.
4. Weighting	Choose weights consistent with theory and use.	Scenarios with equal, expert and/or empirical weights.
5. Aggregation	Decide degree of compensation between dimensions.	Compare sum, geometric mean and thresholds; sensitivity analysis.
6. External validation	Relate scores with observable strategic results.	Convergence, predictive validity, case studies and longitudinal robustness.

Source: elaboration of the author (2026).

4.5. Discussion of the IGPE-IA in light of criticality models

The IGPE-IA architecture inherits from criticality models the idea that risk and importance are multidimensional. Nassar, Du and Graedel (2015) organize risk of supply, environmental implications and vulnerability to restriction; Kosajan, Wen and Wang (2025) update the evaluation and demonstrate the need to differentiate elements. Gemechu *et al.* (2016) incorporate importing exposure and geopolitical risk. IGPE-IA does not replace these approaches: it uses them as a basis and adds processing, manufacturing, science, AI infrastructure, governance and security capabilities.

This enlargement alters the question. A criticality index of materials seeks to identify how critical a raw material is for an economy or technology. The IGPE-IA seeks to organize the potential for conversion of a territorial unit. The first may conclude that a particular element presents high risk; the second must examine whether the unit has access, processing capacity, industry, skills, resilience and governance to respond to this risk. The two perspectives are complementary but not interchangeable.

The framework also incorporates policy benchmarks without automatically turning them into weights. The Critical Raw Materials Act of the European Union establishes, for 2030, references of 10% extractive capacity, 40% processing, 25% recycling and up to 65% of annual demand from a single third country (European Union, 2024). These values demonstrate the

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systemic nature of supply security and can serve as a reference for scenarios; however, they should not be universalized without considering geology, economic scale and strategy of each unit analyzed.

The main contribution of IGPE-IA is to prevent one-dimensional diagnoses. Reserves without refining indicate blocked potential; refining without environmental management indicates fragile capacity; data centers without reliable energy indicate nominal infrastructure; legislation without implementation indicates formal governance; and diversification without technological capacity of suppliers can only redistribute costs. The framework transforms these weaknesses into observable hypotheses for comparative research.

4.6. Link to cybersecurity and personal data protection

Cybersecurity and data protection are included in the IGPE-IA only as governance capabilities required for the reliable operation of cyber-physical infrastructure and AI systems. Third-party management, incident response, auditability, explainability, human oversight, and the work of the data protection officer reduce institutional vulnerabilities (Lima and Alves, 2021; Alves and Conceição, 2025; Santana *et al.*, 2026). These elements do not displace the study's mineral and techno-industrial focus, nor do they imply that data protection alone produces sovereignty; their role is to qualify dimension C1 of the conceptual framework.

4.7. Synthesis of the discussion and evaluation of the propositions

The results support, in theoretical and documentary terms, the main hypothesis: the power associated with rare earth depends on integrated conversion capacity, and not exclusively on reserves or extraction. The hypothesis was not tested economically; therefore, the verb "support" means that triangulation did not refute it and provided compatible mechanisms and evidence.

Proposition P1 received consistent support. The concentration increases from 60% in mining to 91% in refining and 94% in sintered magnets, while the literature on upgrading identifies higher downstream competition. Proposition P2 is also compatible with evidence of environmental costs, liabilities, licensing and potential recycling gains. The P3 proposition was refined: sovereignty in AI era requires material, industrial, scientific, energy, digital, cybernetic and regulatory security, but it can be built by domestic capabilities and by diverse and reliable interdependencies.

The resulting advance is double. The MCGPT explains the transformation in terms of sequence, enablers, bottlenecks and feedback. The IGPE-IA converts this explanation into an

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observation and future measurement agenda, maintaining the boundary between conceptual model and validated index. This separation preserves the rigor of the article and offers two reusable objects by other researchers.

5. FINAL CONSIDERATIONS

This investigation examined how the ability to convert rare earth elements, understood as geoenvironmental assets, into industrial and technological infrastructure influences sovereignty, cybersecurity and geopolitical power in the Age of Artificial Intelligence. The constructed response is that the natural resource acquires strategic value through a conversion chain. Reserves are potential; sustainable extraction makes the potential viable; separation and refining produce functional materials; manufacturing and science aggregate knowledge; AI infrastructure converts components into operational capacity; and governance, security and resilience make this capacity politically reliable.

Documentary data reinforce this interpretation. In 2025, China accounted for approximately 69.2% of world rare earth production. For magnetic elements, their participation in 2024 increased from 60% in mining to 91% in refining and 94% in sintered magnets. The difference shows that the main locus of advantage is not only the underground, but the conversion ecosystem. The contrast between large reserves and low production in economies such as Brazil demonstrates, in a descriptive way, that geological allocation and strategic capacity are distinct categories (USGS, 2026; IEA, 2026).

The first original contribution is the MCGPT, which integrates geoenvironmental base, sustainability, processing, industrial aggregation, science, AI infrastructure, governance, security and geopolitical result. The second is the IGPE-IA, presented with the required caution: a conceptual framework for future evaluation of strategic potential, not an instrument that already measures or classifies countries. Its architecture can guide quantitative research, provided that the indicators are validated, broken down by element, normalized, weighted, submitted to sensitivity analysis and compared with observable results.

The conclusions also requalify sustainability. Waste management, water, energy, radioactive materials, licensing, social participation, traceability and circularity are not peripheral dimensions. They condition continuity, funding, legitimacy and adaptability. Recycling does not eliminate primary extraction in the immediate horizon, but can reduce exposure, expand secondary supply and create industrial skills where the stock of products in use is high.

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The final bond with cybersecurity and data protection broadens the notion of sovereignty. AI infrastructures are cyberphysical and depend on suppliers, data, networks and people. The protection of confidentiality, integrity, availability and recoverability must accompany material security. The governance function of the controller/DPO discussed by Lima and Alves (2021) offers an institutional bridge for accountability in the processing of personal data, although it does not replace the technical management of cybersecurity or broad governance of the AI.

5.1. Insights and authorial propositions arising from the research

To favor cumulative scientific knowledge, the main insights are formulated below as theoretical-interpretative propositions. They synthesize the results of this investigation and can be cited, criticized and tested by further research; they are not presented as universal laws nor as causally estimated relationships.

Insight 1 – The geopolitical advantage of rare earth depends less on the isolated magnitude of the reserve than on the density of installed capacities between the mineral deposit and the final technology.

Insight 2 – In knowledge-intensive chains, downstream bottleneck control can produce greater strategic influence than upstream abundance.

Insight 3 – Socio-environmental sustainability functions as infrastructure of productive continuity: unsustainable practices can generate apparent capacity in the short term and strategic fragility in the long term.

Insight 4 – The sovereignty in Artificial Intelligence is partially mineral, industrial, energy, digital, cybernetic and regulatory; it cannot be inferred only by the performance of models or by the volume of computing.

Insight 5 – Geoenvironmental conversion has a limiting link logic: a critical deficiency in separation, manufacturing, energy, competencies or governance can restrict the value of abundant capacities in the other stages.

Insight 6 – Diversifying mines without diversifying refining, metallization, equipment and magnets displaces geographical dependence, but does not eliminate technoindustrial dependence.

Insight 7 – Data protection, auditability and cyber-resilience are the layer of trust that converts digital infrastructure into sustainable autonomy.

Insight 8 – An index on strategic potential should diagnose capabilities and vulnerabilities before ordering countries; rankings prior to validation can turn methodological uncertainty into false precision.

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Together, these propositions allow the article to be used as a basis for studies on countries rich in resources, industrial powers, supply alliances, mineral corridors and AI policies. The general hypothesis suggested for testing is that the interaction between conversion capacities explains better results of autonomy and influence than any isolated indicator of reserve, production or investment.

5.2. Scientific and practical implications

Scientifically, the MCGPT offers a common language for connecting geosciences, industrial ecology, global value chains, AI studies, cybersecurity and international relations. The IGPE-IA offers a bridge between theory and empirical research. Both can be applied comparatively, but the choice of the unit of analysis must recognize that real chains cross borders and that alliances can internalize capabilities that no country has alone.

For governments, the model guides bottleneck diagnoses and avoids policies focused exclusively on mining licenses. Consistent strategies need to articulate geological knowledge, environmental standards, processing, energy, training, industrial demand, financing, contracts, recycling, supplier security and international cooperation. The European CRM benchmarks illustrate this complete chain approach, although they require contextual adaptation.

For companies and investors, the main implication is that project viability depends on ecosystem: equipment, skills, buyers, co-products, purity requirements, traceability and regulatory risk. For scientific institutions, the framework identifies green separation agendas, alternative materials, waste recovery, metrology, industrial cybersecurity and data governance.

5.3. Limitations and future research agenda

The first limitation arises from the documentary and qualitative design. The evidence was produced by different methods, years and units; therefore, the investigation identifies plausible mechanisms, but does not estimate causal effects. The second is data asymmetry. Information on refining, purity, metallization, magnets, stocks, equipment and contracts is often incomplete or commercial. The third is the pace of change: export controls, projects and capabilities can change quickly.

The fourth limitation is material. Rare earth elements constitute only a portion of the infrastructure of the AI, which also depends on copper, silicon, gallium, germanium, lithium, nickel, graphite and other materials. The MCGPT may be extended, but indiscriminate mineral inclusion will require specific modules to avoid loss of accuracy. The fifth limitation is institutional:

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sovereignty and power are not automatic results of productive capacity; they depend on political decisions, alliances, legitimacy and context.

The future agenda should follow four lines. First, qualitatively validate the MCGPT by contrasting case studies and process tracing, including China, Brazil, Australia, the United States, the European Union and mining alliances. Second, submit the IGPE-IA dimensions to Delphi and content validity analysis. Third, build longitudinal base broken down by element and stage of the chain, with uncertainty analysis and multiple weighting schemes. Fourth, test whether conversion scores predict results such as downstream participation, export complexity, continuity in the face of shocks and recovery time.

It is concluded that rare earth elements are strategic geoenvironmental assets because they articulate nature, technology, territory, environment and power. The competitive advantage depends on the aggregation of value throughout the chain; the MCGPT theoretically explains this transformation; and the IGPE-IA provides a conceptual basis for future quantitative research to operationalize it. The next step is not to produce a premature ranking, but to validate constructs, build comparable data and test, with transparency, under which conditions natural resources become technological sovereignty and geopolitical influence.

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