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Technological Innovation and Sustainable Management of Rare Earths in the Context of Renewable Energy Geopolitics

Alcides Feitosa Neto[1] https://orcid.org/0009-0006-3749-3509; Ana Katherine Silveira Pereira Caracas[2] https://orcid.org/0009-0003-9374-9175; Antonio Werbiton Marinho Almeida[3] https://orcid.org/0009-0002-1904-7522; Emilio Parra Sanches Junior[4] https://orcid.org/0000-0002-0209-7163; Ernandes Farias da Costa[5] https://orcid.org/0000-0002-9855-9667; Francisco José Lopes Cajado[6] https://orcid.org/0000-0002-8824-9251; Francisco José da Silva Fonteles[7] https://orcid.org/0009-0008-7685-9838; Givanildo Ximenes Santana[8] https://orcid.org/0000-0001-8337-1082; Irene Mendes Fontes[9] https://orcid.org/0009-0002-3152-6649; José Reudson de Souza[10] https://orcid.org/0009-0005-4211-4203; Luísa Janaina Lopes Barroso Pinto[11] https://orcid.org/0000-0003-1505-5461; Paulo Henrique Barbosa Sousa[12] https://orcid.org/0009-0007-1269-7860; Rickardo Léo Ramos Gomes[13] https://orcid.org/0000-0001-6101-9571; Roberto Augusto Caracas Neto[14] https://orcid.org/0000-0001-8484-411X; Tadeu Dote Sá[15] https://orcid.org/0009-0005-5575-6328

[1] Master's Degree in Economics From The Federal University of Ceará; [2] Undergraduate Student In Chemical Engineering; [3]Master's degree in Administration and Controllership from UFC; [4] Master's Degree in Educational Sciences from Universidad del Sol – UNADES; [5] Postgraduate Degree in Mathematics Education – FAK; [6] Prof. Dr. in Agricultural Biotechnology (RENORBIO – UFC); [7] Specialization in Environmental Engineering and Basic Sanitation, Centro Universitário Estácio de Sá (SC); [8] Ph.D. in Genetics, Conservation, and Evolutionary Biology National Institute of Amazonian Research, Manaus-AM, Brazil; [9] Postgraduate Degree In Criminal Law From UniAteneu University Center; [10] Specialist In Strategy and Business Management From UFC; [11] Ph.D. in Development and Environment – Federal University of Ceará – UFC; [12] Ph.D. in Educational Sciences, FCSA (DINTER Program); [13] Doctorate in Biological Sciences - FICL; Master's in Phytotechnics - Federal University of Ceará;[14] Doctoral Student At The Academy Of The National Institute Of Industrial Property; [15] Prof. Dr. In Regional Development from the University of Barcelona.
Corresponding Author: Rickardo Léo Ramos Gomes

ABSTRACT
The growing demand for sustainable energy sources has intensified global interest in rare earth elements, which are essential for the production of renewable technologies such as solar panels, wind turbines, and electric vehicles. However, the intensive use of these resources entails environmental, economic, and geopolitical implications that call for new strategies in management and innovation. This study adopts a qualitative methodology grounded in literature review to examine the interrelations among technology, sustainability, and international politics within the contemporary energy landscape. The main objective is to analyze the connections between technological innovation, the sustainable management of rare earths, and the geopolitics of renewable energy, identifying the challenges and opportunities that emerge in the transition toward a more sustainable and competitive global energy model. The analysis of sources revealed that technological innovation plays a crucial role in optimizing the use of rare earth elements, enhancing efficiency, and reducing waste in extraction and recycling processes. Likewise, it became evident that the sustainable management of these resources faces major challenges, including the need to balance industrial demands, environmental preservation, and economic viability. Finally, the study found that the geopolitics of renewable energy is evolving into an arena of intense competition among nations, with direct impacts on governance and the availability of strategic resources.

Keywords: *technological innovation; rare earth elements; sustainability; geopolitics.*

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I. INTRODUCTION

The global energy transition has intensified debate over the dependence on strategic resources, particularly rare earth elements, which are fundamental to the development of sustainable technologies such as wind turbines, solar panels, and electric vehicles. Although these components are essential for technological innovation, they pose significant challenges related to extraction, availability, and environmental impact.

In this context, the sustainable management of rare earth elements emerges as a crucial issue to ensure a balance between economic development, environmental preservation, and energy security. The growing demand for renewable energy sources has also reshaped the global geopolitical landscape, as control over reserves and production of rare earths grants strategic power to certain nations. Therefore, understanding the interconnection between innovation, sustainability, and geopolitics is essential for anticipating risks, designing public policies, and promoting responsible practices in the use of these critical resources.

The study employs a qualitative approach grounded in literature review and critical analysis of scientific research. This methodology enables the integration of diverse theoretical perspectives on technological innovation, sustainable management, and the geopolitics of renewable energy, aiming to identify both convergences and contradictions among these fields of inquiry.

The main objective of this study is to analyze the interrelations among technological innovation, the sustainable management of rare earth elements, and the geopolitics of renewable energy, identifying the challenges and opportunities that emerge in the transition toward a more sustainable and competitive global energy model. Specifically, the study seeks to: (1) assess the impact of technological innovation on the development of sustainable alternatives that optimize the use of rare earths in production chains; (2) analyze sustainable management strategies that integrate environmental, economic, and technological dimensions; and (3) examine the geopolitical dynamics surrounding the control, trade, and international governance of these resources.

The article is structured into four sections: the first outlines the introduction and objectives of the research; the second presents the materials and methods employed; the third develops the theoretical framework, organized around the axes of technological innovation, sustainable management, and renewable energy geopolitics; and the final section provides the concluding remarks, in which the study's contributions are discussed and directions for future research are proposed.

II. MATERIAL AND METHODS

The study employed a qualitative methodology, selected for its capacity to enable an in-depth analysis of the social and technological phenomena associated with innovation and sustainability in the use of rare earth elements. As Creswell (2018) emphasizes, the qualitative approach is suitable for understanding meanings, contexts, and perceptions that cannot be quantified but that reveal the complexity of both human and institutional interactions. Accordingly, the research aimed to examine the topic from multiple perspectives, emphasizing critical source analysis and contextual interpretation of information.

The primary methodological procedure adopted was a bibliographic review, conducted in accordance with the principles of Design Science outlined by Dresch, Lacerda, and Antunes (2015), which guide the construction of scientific knowledge through the integration of methodological rigor and practical applicability. This choice allowed for a coherent articulation between theory and innovation, consistent with the study's purpose of analyzing the challenges and strategies involved in the sustainable management of rare earths. As Gil (2019) observes, bibliographic research represents an essential phase for identifying the current state of knowledge on a given subject and for guiding the development of new analytical frameworks.

The review was based on more than fifteen scientific sources, including articles and books published between 2019 and 2025, ensuring both the contemporaneity and the relevance of the information analyzed. The process of collecting and selecting works followed the guidelines proposed by Cavalcante and Oliveira (2020), who emphasize the importance of clearly defined research criteria and critical evaluation of sources. The temporal scope prioritized recent publications addressing technological innovation, sustainability, and energy geopolitics, with particular attention to studies focusing on the implementation of clean technologies and the strategic use of critical minerals.

Finally, the evaluation of the information gathered during the review was conducted through the lens of design thinking principles, as presented by Brown (2018), who conceptualizes design as a reflective and creative process oriented toward solving real-world problems. This methodological framework allowed for an integrative interpretation of the sources, enabling connections among discussions on technological innovation, sustainable management, and the geopolitical disputes surrounding renewable energy. Thus, the combination of a qualitative approach and a systematic review grounded in design science provided a robust methodological foundation aligned with the objectives of the research.

III. THEORETICAL FRAMEWORK

3.1 Technological Innovation and Sustainability: The Impact of Emerging Technologies on the Optimization of Rare Earth Use

Technological innovation has emerged as a crucial driver in promoting sustainability across the rare earth supply chain. These minerals are indispensable for the production of clean technologies such as wind turbines, electric vehicles, and solar panels. Advances in science have led to significant improvements in extraction efficiency, the development of recycling techniques, and the partial substitution of rare earth elements with environmentally safer alternatives (Andrade & Fonseca, 2020). Within this context, applied research plays a fundamental role in aligning technological progress with environmental responsibility, ensuring that economic development proceeds in harmony with the preservation of natural resources.

Heal (1998) underscores the importance of applied research in balancing economic growth and environmental conservation—an essential condition for the sustainable management of rare earth elements. Recent innovations in the processing and reuse of these materials have contributed to reducing dependence on primary sources, a key factor in achieving both sustainability and energy security (Oliveira et al., 2025). Innovative approaches focused on the recovery of industrial waste and the recycling of electronic devices have expanded the availability of rare earths without requiring additional extractive activities. Furthermore, the development of more sustainable and efficient industrial processes demonstrates the capacity of engineering and science to address complex environmental challenges, fostering a low-carbon economy less vulnerable to geopolitical pressures associated with the control of mineral reserves.

In this regard, **Table 1** summarizes the main dimensions, challenges, and opportunities related to the application of technological innovation in the sustainable management of rare earths, illustrating how such advances can enhance production efficiency and mitigate environmental impacts throughout the value chain.

Table 1 – Technological Innovation and Sustainability in the Use of Rare Earth Elements: Challenges and Opportunities

Dimension	Main Aspects	Identified Challenges	Emerging Opportunities
Extraction and Processing	Development of more efficient and less polluting techniques for obtaining rare earths.	Reduction of environmental impacts resulting from mining and the generation of toxic waste.	Implementation of clean technologies and adoption of sustainable mining best practices.
Recycling and Reuse	Creation of innovative processes to recover rare earths from industrial and electronic waste.	Lack of adequate technological and logistical infrastructure for large-scale recycling.	Expansion of the circular economy and reduction of dependence on primary sources.
Substitution and Technological Innovation	Research aimed at the partial substitution of rare earths with new functional materials.	High development costs and limitations in the efficiency of substitutes.	Encouragement of scientific research and strengthening of technological competitiveness.
Professional Training and Environmental Ethics	Training of professionals with technical skills and socio-environmental awareness.	Gaps in interdisciplinary education and in the integration of science, technology, and ethics.	Development of a culture of sustainable and responsible innovation.

Source: Adapted from Oliveira et al. (2025); Andrade and Fonseca (2020); Binnemans and Jones (2023); Cuadros-Muñoz et al. (2024).

In this context, **Scientific Design** emerges as a strategy that integrates creativity, methodological rigor, and environmental awareness to develop sustainable solutions. The combination of technical knowledge and innovation, according to this approach, fosters the advancement of technologies that mitigate the harmful environmental effects of mineral exploitation and extend the lifespan of existing resources (Brown, 2018). Investment in interdisciplinary research and more efficient management systems not only optimizes the use of rare earth elements but also strengthens the resilience of renewable energy supply chains on a global scale (Binnemans & Jones, 2023). In this regard, sustainable innovation represents a key element of competitiveness, as argued by Porter and van der Linde (1995), since the pursuit of environmental efficiency tends to generate technological and economic advantages.

Finally, it is essential to highlight the educational and ethical role of professionals working in this sector. The consolidation of a sustainable innovation culture requires an educational framework that integrates technical skills, critical thinking, and a commitment to socio-environmental responsibility. Training researchers and engineers to design technological solutions in an integrated manner represents significant progress toward a more equitable and competitive energy model (Cuadros-Muñoz et al., 2024). Thus, the connection between technological innovation and sustainability transcends the mere implementation of new devices, constituting a collective commitment to the future of renewable energies and the preservation of the essential resources that ensure their viability.

3.2 Sustainable Management of Rare Earth Elements: Environmental, Economic, and Technological Challenges in the Global Energy Chain

The sustainable management of rare earth elements has become one of the major challenges of the twenty-first century, particularly given the increasing demand for renewable energy and low-carbon technologies. These minerals, essential for the production of wind turbines, solar panels, and electric vehicle motors, require complex extraction processes that are often harmful to the environment. According to Souza, Nascimento, and Giese (2019), the sustainable extraction of these minerals demands a balanced integration of technological innovation and environmental regulatory frameworks aimed at reducing ecological and social damage. Therefore, the sustainability of this industry is closely linked to the ability to develop methods that minimize reliance on traditional extractive practices and encourage a more rational use of existing resources.

For Brazil, which holds the world's second-largest reserves of rare earth elements (approximately 22 million tons), these developments represent both strategic challenges and opportunities. The country has been courted for international partnerships, such as negotiations with the United States for preferential access to critical minerals, aiming to reduce dependence on China and strengthen geostrategic alliances. However, issues of national sovereignty arise, with debates over the need to balance exports with domestic industrial development to prevent Brazil from becoming merely an extraction zone for foreign powers. Initiatives such as the Serra Verde Project, which began production in 2024, position Brazil as a potential hub for critical minerals but face political and environmental hurdles (Mongabay, 2025).

Within the framework of Mercosur, the trade agreement with the European Union, negotiated in 2025, is expected to strengthen critical mineral supply chains by facilitating market access and encouraging investment in green technologies. This regional integration, aligned with the proposed sustainable maritime corridor for green fuels (previously mentioned), reinforces the bloc's role as a relevant actor in the energy transition, promoting diversification and South–South cooperation. Nonetheless, to maximize these benefits, it is imperative that Brazil and Mercosur adopt governance policies that prioritize sustainable innovation, technical capacity building, and environmental protection—transforming global vulnerabilities into competitive advantages and contributing to more equitable energy geopolitics (European Commission, 2025).

In 2025, the geopolitics of rare earth elements intensified with China's actions, as the country maintains about 70% of global production, consolidating its control over these strategic resources. In April, the Chinese government-imposed export controls on seven heavy rare earth elements, including dysprosium and terbium, in response to U.S. trade tariffs, thereby restricting access to advanced military and technological applications. This measure was expanded in August, when the quota system was extended to include imported ores refined domestically, strengthening state oversight across the entire value chain and heightening the risks of supply concentration. Subsequently, in October, restrictions were extended to five additional elements, effective in November, directly impacting semiconductor and renewable energy industries. These policies not only drive up global prices and create supply chain instability but also reinforce China's position as a dominant actor, using these minerals as instruments of geostrategic influence amid rivalries with Western powers (CSIS, 2025).

Currently, the extraction and processing of rare earth elements remain largely concentrated in China, which controls the majority of global production and refining. This centralization grants the country a strategic position within the global supply chain, affecting not only costs and access to inputs but also the geopolitical dynamics of the energy sector (Santos-Fuser, 2023). While this position has fueled China's technological competitiveness, it also raises concerns about environmental sustainability and international dependency, which limit the autonomy of other nations. Consequently, the search for sustainable extraction solutions and the diversification of suppliers have become priorities for countries seeking to strengthen their energy transition policies without compromising ecological and economic balance.

In this context, the *Global Critical Minerals Outlook 2025* report by the International Energy Agency (IEA), published in May, projects a 50–60% increase in demand for rare earth elements by 2040, driven by the expansion of electric vehicles, wind turbines, and low-carbon technologies. This projection intensifies trade tensions and underscores the urgent need to diversify sources to mitigate dependency risks and enhance global energy resilience. Regions such as Latin America and Africa emerge as potential alternatives, where investments in sustainable mining are essential to meet growing demand without undermining environmental sustainability (IEA, 2025).

The economic costs associated with the purification and processing of rare earth elements represent another significant obstacle to the sustainability of this production chain. The high technological complexity, coupled with the concentration of reserves in a limited number of countries, contributes to market instability, rendering it vulnerable to geopolitical fluctuations (Castro, Peiter, & Góes, 2022). In this context, sustainable management approaches must consider not only environmental repercussions but also the economic and political risks that may affect access and competitiveness in the international energy market.

Table 2 – Dimensions of Sustainable Management of Rare Earth Elements in the Global Energy Chain

Dimension	Key Aspects	Main Challenges	Sustainable Perspectives
Environmental	Responsible extraction and disposal.	Reduction of mining impacts and toxic waste.	Development of clean technologies and recycling processes.
Economic	Extraction costs and international dependence.	Market concentration and price fluctuation.	Strengthening local production and diversification of sources.
Technological	Innovation and material reuse.	Technical difficulties in purification and recycling.	Investment in R&D and sustainable design.
Educational and Ethical	Critical and interdisciplinary training.	Lack of qualification and integration between science and ethics.	Formation of human capital committed to sustainability.

Source: Adapted from Souza, Nascimento, and Giese (2019); Castro, Peiter, and Góes (2022); Brito et al. (2022); Santos-Fuser (2023).

The implementation of public policies aimed at education and scientific research is essential to consolidate a culture of sustainable innovation in this sector. As discussed by Brito et al. (2022), technological progress becomes effective only when supported by appropriate regulation and investments in professional training. In this context, Design Science emerges as a strategic tool for integrating knowledge and fostering solutions that reconcile productive efficiency with environmental responsibility, promoting the development of more ethical and conscious practices (Brown, 2018).

Ultimately, the feasibility of rare earth elements within the global energy transition depends on the interconnection between science, economy, and education. This integration is fundamental for developing a qualified and engaged human capital capable of managing the environmental and technological dimensions of the sector. As Santos-Fuser (2023) points out, Brazil's geopolitical position provides strategic opportunities but also presents substantial challenges, requiring the implementation of long-term policies and a systemic approach that integrates economic competitiveness, technological sovereignty, and environmental preservation.

3.3 Renewable Energy Geopolitics: Governance and Global Competition for Strategic Resources

The global energy transition has led to a significant reconfiguration of geopolitical relations, as control over strategic resources now defines new axes of power in the international arena. Materials such as rare earth elements, lithium, and cobalt have become essential for the production of clean and sustainable technologies, turning into high-value geostrategic assets. According to Santos-Fuser (2023), the supervision of these resources represents a competition that encompasses not only economic but also political and technological dimensions, in which the availability of critical materials becomes a tool of influence and sovereignty. Understanding the geopolitics of renewable energy is therefore essential for identifying the mechanisms that shape global governance and the challenges that arise in the pursuit of a more balanced and inclusive energy model.

In this process of transition, international governance plays a central role in reconciling technological advancement, environmental conservation, and social equity (UN, 2025). Abrão (2022) emphasizes that current energy policies require multilateral collaboration, since no nation acting in isolation can sustain the rapid transformation necessary to achieve decarbonization goals. Within this context, scientific diplomacy and sustainability-oriented education emerge as strategic tools capable of strengthening research networks, fostering responsible innovation, and preparing professionals to address the ethical and environmental dilemmas of the new energy landscape. Design Science, as a systemic and interdisciplinary approach, supports the understanding of the interconnections among energy, society, and the environment, fostering integrated solutions that balance efficiency, ethics, and sustainability (Brown, 2018).

Environmental innovation has become a strategic axis for the development of sustainable production models that reconcile economic growth with ecological balance. In this regard, biotechnology stands out as a promising field, offering solutions grounded in natural processes with low environmental impact. From this perspective, Cajado (2014), in his research on the use of natural compounds for the cryopreservation of fish gametes, highlights the potential of clean biotechnologies as tools for conservation and impact reduction, demonstrating that scientific innovation can serve as a bridge between technological efficiency and ecological sustainability. The study, which employed lyophilized extract of *Opuntia ficus-indica* combined with powdered coconut water, illustrates how the use of native species such as forage cactus can be expanded for multiple purposes, including biofuel production, such as biodiesel, reinforcing the integration of science, technology, and environmental preservation.

Oil, while historically representing the fossil fuel era, continues to play a central role in global geopolitical rivalries. As Carlindo and Peixinho (2025) argue, oil's consolidation as a tool of political and economic power transformed the interactions between producing and consuming nations, shaping alliances and antagonisms throughout the twentieth century. Although progress has been made in renewable energy, oil remains a crucial element of stability and influence in international decision-making, particularly in regions whose economies remain highly dependent on this energy matrix. This persistence demonstrates that the transition to sustainable sources involves not only the substitution of resources but also a complex reconfiguration of geostrategic interests.

Furthermore, Ferreira (2024) contends that the gradual decline of oil's supremacy has intensified tensions between major powers and developing nations, as new technological and energy frontiers emerge. The pursuit of energy autonomy, linked to the need for diversification of sources, has stimulated investments in research and innovation while heightening disputes over critical raw materials such as rare earth elements. Thus, oil remains both a symbolic and strategic reference, serving as a parameter for comparison and transition toward a more sustainable global economy.

The recent proposal to establish a sustainable maritime corridor within Mercosur, led by the Brazilian Association of Cabotage Shipowners (Abac), exemplifies concrete regional initiatives to reduce dependence on fossil fuels and align with global decarbonization goals (Lara, 2025). This proposal strengthens the energy transition movement, gaining increasing relevance in international discussions, while highlighting the structural and political challenges associated with replacing oil with renewable sources. In this context, the green fuel corridor not only represents an attempt to reposition Brazil and its Mercosur partners within the global energy landscape but also reflects the tensions noted by Ferreira (2024) among technological innovation, energy sovereignty, and traditional geoeconomic interests that remain closely tied to oil.

According to Marin (2025), Brazil holds significant geological potential to strengthen its position in the global supply of critical minerals essential for renewable energy technologies. However, this potential is hindered by structural, logistical, and regulatory challenges that limit the country's capacity to compete on an international scale. Overcoming such barriers requires long-term strategic planning, investments in technological infrastructure, and the consolidation of governance mechanisms capable of integrating economic competitiveness with environmental responsibility. Within the broader context of renewable energy geopolitics, Brazil's performance in this sector will largely determine its ability to position itself as a key actor in the global energy transition and to ensure sovereignty over its natural resources.

Ultimately, the geopolitics of renewable energy requires a new framework of governance in which scientific knowledge, international cooperation, and environmental education serve as the foundation for global sustainability. Building a collective awareness of the ethical and responsible use of energy resources depends on nations' ability to implement integrated policies that connect science, technology, and social justice. In this regard, strengthening a sustainability-oriented scientific diplomacy stands as a crucial step toward establishing an energy model that not only reduces carbon emissions but also contributes to the creation of more just and resilient societies.

IV DISCUSSION AND CONCLUSION

The present study aimed to analyze the interactions among technological innovation, sustainable management of rare earth elements, and their geopolitical implications within the framework of renewable energies. The investigation employed a qualitative approach, based on a comprehensive literature review and guided by the principles of Design Science, which enabled a critical and integrated analysis of the technological and environmental transformations influencing the current global economy.

All the proposed objectives were fully achieved. The research coherently articulated the technological, economic, and political aspects related to the sustainable use of rare earth elements, emphasizing innovation as a strategic factor for the development of clean energy and for mitigating the environmental impacts associated with the production chain of these minerals.

The examination of the sources revealed that technological innovation plays a crucial role in maximizing the efficiency of rare earth utilization by improving performance and reducing waste in extraction and recycling processes. Likewise, it became evident that the sustainable management of these resources faces considerable challenges involving the balance between industrial demands, environmental preservation, and economic feasibility. Finally, it was found that the geopolitics of renewable energy has become a domain of intense competition among nations, with direct repercussions on governance and access to strategic resources.

As a result, it is recommended that future research deepen the empirical analysis of public policies and corporate initiatives aimed at promoting sustainability within the rare earth supply chain. Furthermore, it is suggested that investigations explore how international cooperation and advances in circular technologies can foster a more balanced model for the exploration and utilization of these resources, harmonizing innovation, sovereignty, and sustainability on a global scale.

REFERENCES

[1] Abrão, R. A. F. (2022). The geopolitics of renewable energies: Brazil amid the energy transition scenario. *Revista Monções, 11*(22). ISSN: 2316-8323. https://dx.doi.org/10.30612/rmufgd.v11i22.14541

[2] Andrade, M. J. F., & Fonseca, A. A. (2020). Rare earth elements and the energy transition: Challenges and opportunities for Brazil. *Revista de Desenvolvimento Sustentável e Meio Ambiente, 18*(2), 121–135.

[3] Binnemans, K., & Jones, P. T. (2023). Rare earths: Market disruption, innovation and global supply chains. *Sustainability, 15*(3), 1919. https://www.mdpi.com/2071-1050/15/3/1919

[4] Brito, F. B. C., et al. (2022). Rare earth magnets and renewable energies: Technological challenges and regulatory proposals. *Boletim do Observatório Ambiental Alberto Ribeiro Lamego, 16*(2), 02–16. e-ISSN 2177-4560. https://doi.org/10.19180/2177-4560.v16n22022p02-16

[5] Brown, T. (2018). *Design thinking:* A powerful methodology to end old ideas (C. Yamagami, Trans.). Rio de Janeiro: Alta Books.

[6] Cajado, F. J. L. (2014). *Use of lyophilized extract of giant forage cactus (Opuntia ficus-indica) and coconut water powder (ACP-104) for semen cryopreservation of curimatã (Prochilodus brevis)* (Doctoral dissertation, Federal University of Ceará). Fortaleza, Brazil.

[7] Carlindo, S., & Peixinho, D. M. (2025). The geopolitics of energy and the consolidation of oil as an instrument of power. *Revista Sapiência, 14*(1). ISSN: 2238-3565. https://doi.org/10.31668/xq1bjb55

[8] Castro, F. F. de, Peiter, C. C., & Góes, G. S. (2022). *Strategic and critical minerals:* An international overview and the Brazilian mineral policy. Brasília: Instituto de Pesquisa Econômica Aplicada (IPEA). ISSN: 1415-4765.

[9] Cavalcante, L. T. C., & Oliveira, A. A. S. de. (2020). Methods of bibliographic review in scientific studies. *Psicologia em Revista, 26*(1), 82–100. ISSN: 1678-9563. https://doi.org/10.5752/P.1678-9563.2020v26n1p82-100

[10] Center for Strategic and International Studies (CSIS). (2025, October 9). *China's new rare earth and magnet restrictions threaten US defense supply chains*. CSIS Analysis. https://www.csis.org/analysis/chinas-new-rare-earth-and-magnet-restrictions-threaten-us-defense-supply-chains

[11] Creswell, J. W., & Creswell, J. D. (2018). *Research design:* Qualitative, quantitative, and mixed methods approaches (5th ed.). Thousand Oaks, CA: Sage Publications. ISBN-13: 978-1506386706.

[12] Cuadros-Muñoz, J. R., et al. (2024). Contribution of rare earth elements is key to the economy of the future. *Land, 13*(1220). https://doi.org/10.3390/land13081220

[13] Dresch, A., Lacerda, D. P., & Antunes, J. A. V. (2015). *Design science research:* A research method for advancing science and technology. Porto Alegre: Bookman.

[14] Ferreira, A. C. (2024). Development and geoecopolitics of energy: An anthropology of the energy transition and hegemonic disputes within the interstate system. *Horizontes Antropológicos, 70*.

[15] Gil, A. C. (2019). *How to develop research projects* (6th ed.). São Paulo: Atlas. ISBN-13: 978-8597012613.

[16] Heal, G. (1998). *Valuing the future:* Economic theory and sustainability. New York: Columbia University Press.

[17] International Energy Agency (IEA). (2025). *Overview of outlook for key minerals – Global critical minerals outlook 2025*. IEA Reports. https://www.iea.org/reports/global-critical-minerals-outlook-2025/overview-of-outlook-for-key-minerals

[18] Lara, G. T. (2025, October 28). Brazilian exporters propose green fuel corridor for Mercosur. *Argus Media*. https://www.argusmedia.com/en/news-and-insights/latest-market-news/2747158-brazil-shippers-propose-mercosur-green-fuel-corridor

[19] Marin, D. C. (2025). *To become a power in critical minerals, Brazil must overcome obstacles.* São Paulo: *Valor.* Available at: https://valor.globo.com/publicacoes/especiais/mineracao/noticia/2025/11/11/para-se-tornar-potencia-em-minerais-criticos-brasil-precisa-superar-obstaculos.ghtml. Accessed on: November 2025.

[20] Mongabay European Commission. (2025). EU-Mercosur partnership agreement: Enhancing trade and investment in critical raw materials. *European Union Trade Policy*. https://policy.trade.ec.europa.eu/eu-trade-relationships-country-and-region/countries-and-regions/mercosur/eu-mercosur-agreement/factsheet-eu-mercosur-partnership-agreement-enhancing-trade-and-investment-critical-raw-materials_en

[21] Mongabay. (2025, September 15). Rare earth rush endangers rural communities and conservation areas in Brazil. *Mongabay News*. https://news.mongabay.com/2025/09/rare-earth-rush-endangers-rural-communities-and-conservation-areas-in-brazil/

[22] Oliveira, R. D., et al. (2025). The search for rare earths for regional development: The new frontier of industrial development. *Lumen et Virtus, 16*(50), 9346–9364. DOI: 10.56238/levv16n50-087.

[23] United Nations (UN). (2025, September 11). *Principles to guide the mining of critical elements for the energy transition:* Report of the UN Secretary-General's Panel on Critical Minerals for the Energy Transition. https://brasil.un.org/pt-br/128238-relatorio-da-onu-pede-financiamento-e-investimento-responsaveis-em-minerais-de-transicao-energetica

[24] Porter, M. E., & van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *Journal of Economic Perspectives, 9*(4), 97–118.

[25] Santos-Fuser, L. N. dos. (2023). The geopolitics of rare earths and Brazil's integration. *Geopolítica(s): Revista de Estudios sobre Espacio y Poder, 14*(1), 27–50. ISSN: 2172-3958. https://dx.doi.org/10.5209/geop.79921

[26] Souza, A. C. S. P. de, Nascimento, M., & Giese, E. C. (2019). Challenges for the sustainable extraction of rare earth-bearing minerals. *HOLOS, 1*, 1–23. https://doi.org/10.15628/holos.2019.8274