

# Strategic and Critical Minerals: Mining and Industrialization as Catalysts for Economic Development in the Twenty-First Century

Márcio Carneiro Barbosa <sup>1</sup>

<sup>1</sup>(Bachelor's Degree in Military Sciences – Academia Militar das Agulhas Negras (AMAN); Bachelor's Degree in International Relations – Universidade do Sul de Santa Catarina (UNISUL); Higher Technology Degree in Foreign Trade – Universidade do Sul de Santa Catarina (UNISUL); MBA in Business Logistics – Fundação Getúlio Vargas (FGV); MBA in Renewable Energy Management – FBUi / Instituto Euvaldo Lodi (IEL); Postgraduate Degree in Higher Education Teaching – Universidade Federal do Rio de Janeiro (UFRJ); Postgraduate Degree in Public Administration – Universidade Católica de Brasília (UCB); Specialization in National Logistics – Escola Superior de Guerra (ESG); Specialization in Marketing Management – Universidade Veiga de Almeida (UVA); M. Sc. in Military Sciences – Escola de Comando e Estado-Maior do Exército., Brazil)

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## **Abstract:**

**Background:** Strategic and Critical Minerals have become increasingly important in the twenty-first century due to their essential role in advanced technologies and industrial development. In this context, mining and the industrialization of these resources have emerged as significant drivers of economic growth and national competitiveness. This study examines the importance of Strategic and Critical Minerals, including Rare Earth Elements, as catalysts for economic development through industrialization.

**Materials and Methods:** This research adopted a qualitative approach to investigate the extent to which Strategic and Critical Minerals can promote economic development following their industrialization. The study employed a literature and documentary review, drawing upon three categories of sources: (1) publications presenting definitions of Strategic and Critical Minerals; (2) studies describing their industrial and technological applications; and (3) sources addressing the relationship between these minerals and the industrialization process.

**Results:** The reviewed literature demonstrated the broad range of industrial applications associated with Strategic and Critical Minerals, particularly in high-technology sectors. The findings also highlighted the strong connection between the industrialization of these resources and economic development, emphasizing their relevance to technological innovation, industrial expansion, and value-added production chains.

**Conclusion:** The results indicate that Strategic and Critical Minerals possess significant potential to foster economic growth in the twenty-first century, particularly in countries capable of developing, controlling, and integrating their production chains into industrial and technological sectors. Therefore, the industrialization of these resources represents a strategic pathway toward sustainable economic development and enhanced international competitiveness.

**Key Word:** Strategic Minerals; Critical Minerals; Rare Earth Elements; Industrial Development.

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## I. Introduction

Mining activities have historically been employed by humankind as a means of promoting regional economic development. A historical milestone that serves as a reference point was the search for precious metals, particularly gold and silver, between the sixteenth and eighteenth centuries. Through the Age of Exploration, the Iberian kingdoms of Portugal and Spain consolidated their power in Europe based on the mineral wealth extracted from the Americas. Within the framework of the Colonial Pact, Brazil, as a Portuguese colony, became one of the principal suppliers of gold to the Portuguese Crown.

During the eighteenth and nineteenth centuries, with the advent of the First Industrial Revolution (1760–1850) in England, economic and industrial development initially emerged in the British Isles, subsequently spreading throughout Europe and later to other continents. This transformation was largely driven by iron mining, which enabled advances in steelmaking, metallurgy, and numerous technological innovations developed during that period.

As human societies evolved through continuous technological innovation, subsurface resource exploitation facilitated the extraction, production, and extensive use of oil and natural gas, two energy sources that have fueled economic and industrial development from the twentieth century to the present day. As fundamental pillars of national industrialization and economic growth, mining activities have directly contributed to improving the quality of life in societies benefiting from their resources.

In the twenty-first century, mineral resources have attained unprecedented relevance and strategic importance for socioeconomic progress. Disruptive technologies associated with major contemporary innovations are directly linked to the industrial processing of mineral resources that have been previously extracted, benefited, and incorporated into high-technology products, goods, and services.

This context is further reinforced by the recognition that the global energy model, historically based on the intensive use of fossil fuels and other non-renewable energy sources, has generated significant environmental impacts, evidenced by climate change and global warming. These challenges have prompted the international community to pursue an energy transition toward renewable energy systems, whose technological infrastructure depends intrinsically on specialized minerals possessing unique and irreplaceable physicochemical properties.

Equally important, increasing demands for industrial competitiveness and productivity have stimulated the automation of machinery and the digitalization of production processes. Industrial operations have undergone profound transformations driven by digital technologies, robotics, cloud computing, Artificial Intelligence, and other advanced technological innovations.

It is within this context that Strategic and Critical Minerals have emerged as essential inputs for digital, energy, industrial, and scientific-technological transformations. Recognized by the international community as indispensable resources, these minerals have positively influenced multiple production chains, demonstrating their capacity to shape the global geopolitical landscape while strengthening the economic infrastructure of numerous countries.

Through value addition across their extensive production chains, from extraction to industrial processing, Strategic and Critical Minerals have transformed transportation, telecommunications, healthcare, defense, energy, and agro-industrial systems, among other sectors. Their industrial utilization has enabled the production of advanced technological goods and services, meeting the demands of modern societies in increasingly effective and sustainable ways.

Regarding the methodological approach, this study adopted a qualitative research design. In terms of investigative procedures, the research consisted of a bibliographic and documentary review based on national and international publications, scientific articles, governmental reports, multinational institutional documents, and online resources. The consultation and synthesis of these materials made it possible to identify and analyze the most relevant issues associated with the subject under investigation.

Accordingly, the general objective of this study is to analyze how the mining and industrialization of Strategic and Critical Minerals act as catalysts for economic development in the twenty-first century. Based on this analysis, the study seeks to provide insights for the academic community and for political, economic, scientific, and technological institutions, thereby fostering greater awareness of and prioritization for the sustainable strengthening of these minerals' production chains in support of national development.

The specific objectives are: (a) to present the definitions of Strategic and Critical Minerals; (b) to demonstrate the applicability of Strategic and Critical Minerals in high-technology products; and (c) to characterize industrial development derived from these natural resources.

To achieve these objectives, the article is organized into four sections that provide a comprehensive analysis of the importance of Strategic and Critical Minerals as catalysts for industrial development in the twenty-first century. The first section, Introduction, presents the central theme of the study. The second section, Methodology, describes the research approach, including the data collection and analytical procedures adopted. The third section, Theoretical Framework, examines the different definitions of Strategic and Critical Minerals, discusses their diverse industrial applications, and characterizes the relationship between these mineral resources and the industrialization processes through which they contribute to national development.

Finally, the Conclusion section synthesizes the principal findings of the study, providing insights for the academic community as well as political, economic, scientific, and technological institutions. The discussion highlights the advantages associated with the industrialization of Strategic and Critical Minerals and their contribution to the economic and social development of contemporary societies.

## **II. Material And Methods**

The approach adopted in this study was qualitative in nature, as its primary objective was to analyze how the mining and industrialization of Strategic and Critical Minerals act as catalysts for industrial development in the twenty-first century. This approach is widely recognized within the scientific community for its capacity to

provide contextual analyses, enabling a comprehensive understanding of the extent to which Strategic and Critical Minerals influence the industrial development of societies.

Furthermore, qualitative research emphasizes the interpretation and understanding of complex phenomena, making it particularly suitable for investigations involving mineral resources that have significantly contributed to scientific and technological advancement and to the promotion of industrial development.

Regarding the methodological procedures, the study was classified as bibliographic research. This type of investigation is based on the systematic analysis of previously published scientific literature and constitutes one of the fundamental pillars of scientific knowledge production. According to Pereira et al. (2018), bibliographic research contributes to the consolidation of theoretical and methodological frameworks by gathering and interpreting significant contributions related to a specific topic. Similarly, Yin (2016) argues that this method enhances the analytical robustness of a study by grounding discussions in well-established theoretical perspectives.

For the purposes of this review, the research sources were selected and classified into three principal categories: (1) sources presenting different definitions of Strategic Minerals and Critical Minerals; (2) sources characterizing the diverse applications of Strategic and Critical Minerals; and (3) sources examining the interrelationship between these minerals and the industrialization processes associated with such natural resources.

The classification of these sources enabled a deeper understanding of the significance, indispensability, and broad applicability of Strategic and Critical Minerals in industrial processes. The bibliographic and documentary reviews were conducted through the examination of national and international publications, scientific articles, reports from governmental institutions, documents produced by international organizations, and online resources. This comprehensive approach ensured broad coverage of the subject and highlighted the contributions of these resources to the academic community, as well as to political, economic, scientific, and technological institutions, thereby supporting the recognition of Strategic and Critical Minerals as a priority area for fostering national development.

### **III. Theoretical Framework**

This theoretical framework was organized into three subsections. The first subsection presents the definitions of Strategic Minerals and Critical Minerals. The second subsection examines the diverse applications of Strategic and Critical Minerals and their contributions to modern societies. The third and final subsection characterizes the interrelationship between Strategic and Critical Minerals and the industrialization of these mineral resources, highlighting their role in fostering national development.

#### **3.1 Definitions of Strategic Minerals and Critical Minerals**

The continuous pursuit of innovation and global economic growth has accelerated the transition toward Industry 4.0. This phenomenon, which redefines automation paradigms, is intrinsically linked to the availability and development of strategic materials that have emerged as crucial and irreplaceable components for the advancement of modern industries (Oliveira et al., 2025).

In addition, this scenario is reinforced by the urgent need to reduce fossil fuel consumption and mitigate the effects of climate change through the expansion of renewable energy sources. Consequently, the energy transition has revealed a direct relationship between industrial development and specific minerals that are essential for enabling clean energy generation and storage technologies. Within this context, several natural resources have come to be classified as Strategic and Critical Minerals, a status that has become increasingly evident in light of growing long-term global energy demand (IBRAM, 2025).

The literature review revealed that the definitions of Strategic Minerals and Critical Minerals are not standardized across countries, with distinct concepts and interpretations reflecting national policies and priorities. A mineral considered strategic in one country may be regarded as critical in another, and vice versa. Therefore, defining which raw materials should be classified as strategic or critical requires country-specific assessments of each mineral resource and its associated industrial value chains, with the objective of formulating supply strategies capable of meeting domestic and international demands (Castro, Peiter, & Góes, 2022).

The essence of classifying a material as strategic or critical lies primarily in its economic importance and the risks associated with its supply. Imbalances between mineral supply and demand, shaped by technological, economic, and geopolitical dynamics, also contribute to this classification. As production chains evolve and adapt to new circumstances, perceptions regarding which materials should be considered critical may likewise change over time (CEBRI, 2025).

Minerals are generally regarded as strategic when a country possesses reserves capable of supporting highly demanded productive sectors, whether domestic or international, due to their economic and geopolitical relevance (CEBRI, 2025). In China, for example, strategic minerals are considered pillars of economic security and national defense. Since 1959, the country has adopted a protectionist approach aimed at strengthening its

domestic industry through investments in technology and innovation (Gulley, McCullough, & Shedd, 2019, as cited in Tomi, Loredó, & Santos, 2024).

Within the European Union, strategic minerals are defined as those essential for advancing key technologies associated with the energy transition, while also supporting the defense and aerospace sectors. These resources are directly linked to the region’s reindustrialization strategy, which emphasizes the principles of the circular economy and technological diversification (Pope & Smith, 2023).

Strategic mineral resources are widely recognized as possessing substantial economic and geopolitical value for a nation’s economy and security. Their applications extend across both technological and defense-related sectors, simultaneously influencing a country's capacity to compete in international markets and safeguard its national interests. Consequently, such resources are considered fundamental to technological, economic, and social development, particularly for countries endowed with significant mineral reserves within their territories (Araújo, 2023).

The Brazilian Mining Institute (IBRAM) defines strategic minerals as those characterized by significant reserves, production potential, and applicability in sectors of technological and commercial relevance at the national level (IBRAM, 2025). In Brazil, this definition is formally established in Article 2 of Decree No. 10,657 of 2021 (Brazil, 2021).

**Table 1.** Definitions of Strategic Minerals in Brazil

Group	Definitions
<b>Group I</b>	Mineral commodities for which the country depends heavily on imports to supply vital sectors of the economy: <b>Sulfur; Phosphate; Potassium; and Molybdenum.</b>
<b>Group II</b>	Mineral commodities that are important due to their application in high-technology products (both in Brazil and abroad): <b>Cobalt; Copper; Tin; Graphite; Platinum Group Metals; Lithium; Niobium; Nickel; Silicon; Thallium; Tantalum; Rare Earth Elements; Titanium; Tungsten; Uranium; and Vanadium Ore.</b>
<b>Group III</b>	Mineral commodities that possess comparative advantages and are essential to the economy due to their contribution to generating trade balance surpluses: <b>Aluminum; Copper; Iron; Graphite; Gold; Manganese; Niobium; and Uranium.</b>

**Source:** Tomi, Loredó, and Santos (2024) and Bezerra (2025).

Based on the National Mining Plan 2030 (Brazil, 2011), strategic minerals for Brazil were defined according to one of the following three criteria (Brazil, 2011; 2022, as cited in Bezerra, 2025):

- a. Minerals on which the country depends and imports on a large scale, which are essential to vital sectors of the Brazilian economy;
- b. Minerals whose demand is increasing and is expected to expand further in the coming decades due to their application in high-technology products; and
- c. Minerals for which Brazil possesses natural comparative advantages and international leadership in reserves and production.

In general terms, particularly within the geopolitical context of the first half of the twenty-first century, a country capable of controlling its own strategic mineral production chain would enjoy greater autonomy in determining its development trajectory, reducing its dependence on external factors (Oliveira et al., 2025).

Conversely, another category encompasses critical minerals. These resources are frequently referred to as “high-technology minerals” or “green minerals” because of their essential role in the development of clean technologies and in meeting the demands of modern societies. Critical minerals are highly important to industry and are indispensable for renewable energy generation technologies, such as wind turbines and solar panels, while also serving as key components of low-carbon infrastructures and technologies (Hine, Gibson, & Mayes, 2023, as cited in Tomi, Loredó, & Santos, 2024).

In general, minerals are classified as critical according to their importance to strategic production chains, supply constraints, the geographic concentration of reserves, market dominance by a limited number of suppliers, and vulnerabilities associated with geopolitical instability, extreme climate events, environmental accidents, geological limitations, pandemics, and armed conflicts (CEBRI, 2025).

The United States, for example, has a long-standing tradition of examining issues related to the supply of raw materials. In 2018, its list of critical minerals was updated by the Subcommittee on Critical and Strategic Mineral Supply Chains of the National Science and Technology Council (NSTC, 2018). According to this definition, a critical mineral is a non-fuel mineral or mineral material that is essential to economic and national security and is utilized in the manufacture of specific products, whose absence could generate significant consequences for the U.S. economy and national security (Castro, Peiter, & Góes, 2022).

Within the European Union, critical minerals are defined as those that make significant contributions to industrial value chains and constitute vital substances for economic development and the functioning of manufacturing systems. Their supply may be subject to risks associated with mineral and geological scarcity, geopolitical dynamics, trade regulations, and political or infrastructure instability (EC, 2017, 2023; USDE, 2011).

Recognizing this global context, the European Union advanced the Critical Raw Materials Act, establishing production, processing, and recycling targets for its member states while simultaneously pursuing strategic partnerships with supplier countries in Latin America and Africa (Mancin, 2026).

In 2023, the European Commission published an updated list of critical raw materials and critical minerals for the member states of the European Union, as presented in Table 2 below.

**Table 2.** List of Critical Raw Materials According to the European Commission

Feldspar	Rare Earth Elements	Arsenic	Fluorite
Helium	Platinum Group Metals	Cobalt	Copper
Bauxite	Coking Coal	Lithium	Phosphorus
Magnesium	Silicon Metal	Barite	Gallium
Strontium	Beryllium	Germanium	Natural Graphite
Bismuth	Hafnium	Niobium	Titanium Metal
Phosphate Rock	Vanadium	Nickel	Scandium

**Source:** European Commission (EC, 2023).

The European Commission considers that the updated list of critical raw materials may contribute to the following objectives (EC, 2023):

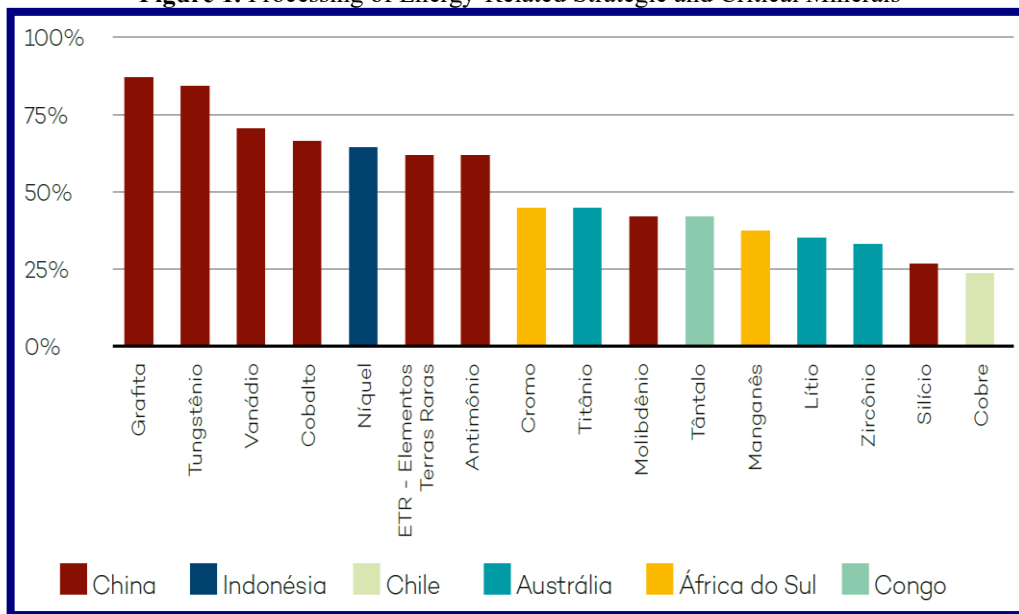
- a. Strengthening the competitiveness of European industry;
- b. Promoting the production of recycled raw materials;
- c. Increasing awareness among member states, businesses, and investors regarding potential risks associated with the supply of these raw materials;
- d. Facilitating the negotiation of trade agreements and the challenge of trade-distorting measures;
- e. Advancing research and innovation initiatives; and
- f. Supporting the implementation of the 2030 Agenda for Sustainable Development and its Sustainable Development Goals.

In India, critical mineral resources are defined as primary or processed mineral materials that are essential to production processes and whose supply may be disrupted due to unavailability or significant price increases. These resources are characterized by limited substitutability, the absence of viable recycling alternatives, and their incorporation into green technologies, high-technology equipment, as well as the aviation and national defense sectors (CSEP, 2022).

Another important aspect in the definition of critical minerals within each country is associated with specific industrial demands and the transition toward a low-carbon economy. In this context, certain minerals are considered indispensable for renewable energy generation and the deployment of clean technologies (Bobba et al., 2020, as cited in Castro, Peiter, & Góes, 2022).

From an international perspective, Figure 1 illustrates the principal countries involved in the processing of Strategic and Critical Minerals, highlighting China's prominent position within global mineral processing value chains.

**Figure 1.** Processing of Energy-Related Strategic and Critical Minerals



Source: Brazilian Mining Institute (IBRAM, 2025).

Not surprisingly, national strategies seek to meet domestic demands through policies that align economic, defense, and public health interests. In this regard, national policies can be understood as responses to increasing international competition driven by technological innovation, while simultaneously reflecting strategic interests aimed at preserving national sovereignty (Uren, 2019; Cuellar, 2013, as cited in Castro, Peiter, & Góes, 2022).

In general, these raw materials constitute essential inputs because they are incorporated into components used in the manufacture of innovative products, including high-performance semiconductors, mobile phones, flat-panel displays, wind turbines, electric vehicles, solar panels, high-capacity batteries, permanent magnets, advanced technological devices, and the broader digital and green infrastructure that underpins the twenty-first-century economy (Blengini, 2020; EC, 2021; Mancin, 2026).

In Brazil, the criteria used to classify Strategic and Critical Minerals can be identified according to the framework established by the Brazilian Mining Institute, as presented in Table 3.

**Table 3.** Criteria for the Relative Classification of Strategic and Critical Minerals

Strategic Minerals	Critical Minerals
Possess significant domestic mineral endowments.	Exhibit substantial demand for domestic production.
Have export demand in either raw or processed forms.	Lack significant domestic mineral endowments relative to demand.
Represent economic importance to the domestic market and are utilized in productive processes that promote value addition within industrial chains.	Depend on imports at different stages of the value chain.
Are applied in the production of high-technology products.	Face risks of supply disruption.
Are essential for economic decarbonization and contribute to the energy transition.	May require specialized processing techniques and highly skilled labor.

Source: Brazilian Mining Institute (IBRAM, 2025).

It should be emphasized that growing geopolitical tensions, marked by a series of export controls on essential materials and technologies, have increased supply risks, demonstrating that disruptions and restrictions affecting the flow of critical minerals are no longer merely theoretical concerns (IEA, 2025).

In addition, within the universe of Strategic and Critical Minerals, Rare Earth Elements occupy a particularly prominent position. This group of 17 chemical elements constitutes a fundamental pillar of emerging technologies and future industrial development. Owing to their unique electronic, magnetic, and optical properties, Rare Earth Elements are indispensable in numerous modern applications and in the manufacture of advanced technological systems (Oliveira et al., 2025; Júnior & Oliveira, 2020, as cited in Santos, 2025).

**Figure 2. Rare Earth Elements**



**Source:** CNN Brasil Infra (Mancin, 2026). **Photograph:** REUTERS/David Becker.

Rare Earth Elements include neodymium and praseodymium, which are used in high-performance permanent magnets for electric motors and wind turbine generators; lanthanum and cerium, which are applied in petroleum refining catalysts and in alloys used for nickel-metal hydride (Ni-MH) batteries; and yttrium and europium, which are employed in phosphors for liquid crystal and light-emitting diode displays (LCDs and LEDs), as well as in lasers, optical fibers, and magnetic resonance imaging equipment. These applications demonstrate the indispensable role of Rare Earth Elements in advancing and consolidating Industry 4.0 technologies (Silva et al., 2017; Filho & Serra, 2014, as cited in Oliveira et al., 2025).

Currently, demand for Rare Earth Elements has intensified due to the growing need for high-purity metals and oxides required in the production of advanced technological goods (Loureiro, 1994, as cited in Souza et al., 2019).

The importance of these materials is not merely quantitative but also qualitative, given that their physicochemical properties are largely irreplaceable. These characteristics ensure the performance, durability, and efficiency of industrial products, making Rare Earth Elements key components for energy security, industrial competitiveness, and technological sovereignty (Karas, 2025).

Therefore, it can be concluded that Strategic and Critical Minerals, including Rare Earth Elements, constitute an indispensable component of the twenty-first century. Their appropriate and timely classification enables a more comprehensive understanding of their strategic value, fostering investments in Research and Development, strengthening scientific and technological sovereignty, and supporting industrialization and economic power for the benefit of the societies in which these resources are developed and utilized.

### **3.2 Applications of Strategic and Critical Minerals**

Mineral resources are classified as non-renewable resources and possess extensive applications across a wide range of industrial sectors, including infrastructure, energy generation, aerospace technology, agriculture, and defense industries (IBRAM, 2025).

According to the International Energy Agency, demand for several Strategic and Critical Minerals continued to increase significantly in 2024. Lithium demand, for example, grew by nearly 30%, while demand for nickel, cobalt, graphite, and rare earth elements increased by approximately 6% to 8% in 2025. This growth was largely driven by energy-related applications, including electric vehicles, battery energy storage systems, renewable energy technologies, and electrical grids. In the case of copper, the rapid expansion of investments in power grid infrastructure in China represented the primary driver of demand growth over the previous two years. For battery-related minerals, including lithium, nickel, cobalt, and graphite, the energy sector accounted for approximately 85% of demand growth during the same period (IEA, 2025, as cited in Bezerra, 2025).

Aluminum, classified as a strategic mineral in Brazil, has numerous applications in the automotive, aerospace, construction, electronics, and packaging industries, among others. Phosphorus, in turn, is essential for the production of NPK fertilizers, which are critical for Brazilian agricultural productivity, particularly in large-scale monoculture systems that require increasing fertilizer inputs. It is also important to recognize that graphite is the non-metallic mineral from which graphene is produced. Graphene consists of a single layer of carbon atoms arranged in a two-dimensional hexagonal lattice and is considered a nanomaterial with significant applications in the electronics, biomedical, and telecommunications sectors (IBRAM, 2025).

Silicon, one of the most abundant minerals in the Earth's crust, also deserves particular attention due to its extensive applications in the energy transition through photovoltaic panels, as well as in glass manufacturing, ceramics, biomedical technologies, semiconductors, and agricultural systems. Titanium, meanwhile, possesses high value-added industrial applications that contribute significantly to national economic development, including

aircraft components such as engines, fuselages, and landing gear; missile systems associated with naval, aerospace, and defense industries; and equipment utilized by the chemical and petrochemical sectors (IBRAM, 2025).

Another resource of considerable importance to modern industry is niobium, a strategic metal with a wide range of industrial and technological applications, particularly in the production of high-performance alloys. Following beneficiation and processing, niobium is employed in the automotive, aeronautical, aerospace, electronics, chemical, and energy-generation industries, as well as in superconducting composite materials (Bezerra, 2025). Its principal application is as an alloying element in specialty steels. Even in very small concentrations, generally below 0.1%, niobium significantly enhances mechanical strength, weldability, and corrosion resistance (CEBRI, 2025).

Another important consideration is that, with the advancement of global production chains, Strategic and Critical Minerals increasingly support not only consumer electronics but also a broad range of sectors, including defense, surveillance, agriculture, infrastructure, pharmaceuticals, and medical technologies (USGS, 2017, as cited in Castro, Peiter, & Góes, 2022). Demand for these resources is expected to increase substantially through 2034, driven by the expansion of electrical infrastructure and the electrification of transportation systems. Under these circumstances, graphite, phosphorus, lithium, and rare earth elements are projected to experience the largest proportional increases in demand, largely as a result of fleet electrification and the growing use of rechargeable battery technologies (Brazil, 2025).

Particular attention should be given to China, which has become increasingly specialized in the industrialization of Critical Minerals throughout the twenty-first century and in the production of mineral-based manufactured goods. These products include essential inputs for a wide variety of technologies associated with energy systems, electronics, transportation, and medical equipment (Barteková & Kemp, 2016; Mancheri, Sundaresan, & Chandrashekar, 2013, as cited in Castro, Peiter, & Góes, 2022).

Finally, the United States of America (USA), the world's largest industrial economy, has identified Strategic and Critical Minerals of national interest whose applications extend across numerous sectors, including industry, defense, energy, telecommunications, transportation, and healthcare, as illustrated in Table 4 below.

**Table 4.** Applications of Critical Minerals in the United States

Commodity mineral	Setores						Principais exemplos de aplicação
	Aeroespacial (não militar)	Defesa	Energia	Telecomunicações e eletrônicos	Transporte (não aéreo)	Outros	
Alumínio	x	x	x	x	x	x	Aeronaves, linhas de transmissão de energia e ligas leves.
Antimônio		x	x	x	x	x	Baterias de chumbo-ácido.
Arsênio		x	x	x		x	Comunicações (arsenieto de gálio).
Barita			x	x		x	Fluido de perfuração de petróleo e gás
Berílio	x	x	x	x		x	Comunicações por satélite, metal berílio para indústria aeroespacial.
Bismuto		x	x	x		x	Produtos farmacêuticos, soldas sem chumbo.
Césio e rubídio	x	x	x	x		x	Aplicações médicas, satélites de posicionamento global, dispositivos de visão noturna.
Cromo	x	x	x	x	x	x	Motores a jato (superligas), aços inoxidáveis.
Cobalto	x	x	x	x	x	x	Motores a jato (superligas), baterias recarregáveis.
Flúor			x	x		x	Produção de alumínio e aço, processamento de urânio.
Gálio	x	x	x	x		x	Radar, diodos emissores de luz (LED), telefones celulares.
Germânio	x	x	x	x		x	Dispositivos infravermelhos, fibra óptica
Grafita	x	x	x	x	x	x	Baterias recarregáveis, armadura corporal.
Hélio				x		x	Imagem de ressonância magnética.
Índio	x	x	x	x		x	Monitores de tela plana, ligas especiais
Lítio	x	x	x	x	x	x	Baterias recarregáveis, ligas de alumínio-lítio (indústria aeroespacial)
Magnésio	x	x	x	x	x	x	Segurança de incêndio para indústria aeroespacial.
Manganês	x	x	x	x	x	x	Produção de alumínio e aço, ligas leves
Nióbio	x	x	x	x		x	Aço de alta resistência para defesa e infraestrutura.

Metais do Grupo Platina	x		x	x	x	x	Catalisadores, superligas para motores a jato.
Potássio			x	x		x	Fertilizante agrícola.
Elementos Terras Raras	x	x	x	x	x	x	Orientação aeroespacial, lasers, fibra óptica.
Rênio	x		x	x		x	Motores a jato (superligas), catalisadores.
Escândio	x	x	x	x		x	Ligas leves, células de combustível.
Estrôncio	x	x	x	x	x	x	Ligas de alumínio, ímãs permanentes.
Tântalo	x	x	x	x		x	Capacitores em telefones celulares, motores a jato (superligas)
Telúrio		x	x	x		x	Dispositivos infravermelhos (visão noturna), células solares
Estanho		x		x		x	Solda, monitores de tela plana (óxido de índio-estanho).
Titânio	x	x	x	x		x	Motores a jato (superligas) e fuselagens (ligas de titânio), aço de alta resistência.
Tungstênio	x	x	x	x		x	Ferramentas de corte e perfuração, catalisadores, motores a jato (superligas).
Urânio	x	x	x			x	Aplicações nucleares, aplicações médicas.
Vanádio	x	x	x	x		x	Motores a jato (superligas) e fuselagem (ligas de titânio), aço de alta resistência.
Zircônio e háfnio	x	x	x	x		x	Revestimento de barreira térmica em motores a jato, aplicações nucleares.

Source: United States Geological Survey (2019)

It can be concluded, at least provisionally, that Strategic and Critical Minerals, including Rare Earth Elements, exert a pivotal influence on the development of disruptive technologies, particularly those associated with the green economy and sustainable technological transitions. The breadth, diversity, and extensive range of applications of these mineral resources provide competitive advantages to countries capable of integrating them into their industrial and economic development strategies. As a result, these resources contribute significantly to shaping the global geopolitical landscape and influencing the balance of power among nations.

### 3.3 Industrial Development Driven by Strategic and Critical Minerals

Mineral raw materials constitute the foundation of industrial value chains and will continue to occupy this position in the future, as mineral commodities are incorporated into virtually all industries at some stage of their production processes (IRTC, 2020, as cited in Castro, Peiter, & Góes, 2022).

Within this context, the mining sector, driven by Industry 4.0, has undergone a remarkable transformation in its practices and operations. The integration of advanced technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), and automation, has reshaped the manner in which mineral extraction and processing activities are conducted. Automation has emerged as a driving force in the mining industry, as autonomous equipment and robotic systems equipped with sophisticated sensors now play a vital role in mining operations. These innovations have not only enhanced operational efficiency but have also improved worker safety by enabling hazardous tasks to be performed without direct exposure to risks (Reis, 2024).

Concurrently, the world is entering a new stage of development characterized by the consolidation of green energy value chains and the widespread adoption of clean and disruptive technologies. Sectors that, until two decades ago, were largely experimental, such as solar photovoltaics, wind energy, rechargeable batteries, and electric vehicles, have assumed a central role in industrial and energy policies. This transformation reflects both the growing concern over climate change and the economic benefits associated with the integration of these technologies into contemporary societies. The so-called “new energy economy” already generates billions of dollars in economic activity and is expected to reshape production systems, labor markets, and global trade patterns (IEA, 2024, as cited in IBRAM, 2025).

Supporting these developments, Strategic and Critical Minerals emerge as key components of this transformation. Far beyond their role as industrial inputs, these resources have increasingly become instruments of geopolitical influence. Competition for their control is reshaping alliances, trade policies, and development strategies. For countries such as Brazil, the challenge is evident: transforming geological potential into geopolitical leadership through robust industrial policies, active diplomacy, and sustained investments in technology and sustainability (Bezerra, 2025). In other words, countries capable of controlling these minerals and, more importantly, their associated value chains may ultimately control the foundations of energy security, industrial competitiveness, and even military autonomy in the coming decades (Mancin, 2026).

For this reason, the development of an effective industrial policy becomes essential, extending beyond the extraction of raw materials to promote the establishment of refining facilities, material processing plants, component manufacturing industries, and Research and Development Centers. The creation of endogenous capabilities is decisive for enabling mineral-producing countries to position themselves competitively within global value chains (IBRAM, 2025).

The importance of this issue is reflected in the fact that the concentration of mineral production and supply has increasingly influenced international geopolitics, leading countries to formulate strategic plans for critical raw materials through the adoption of commercial and industrial policies designed to secure access to these resources (Castro, Peiter, & Góes, 2022).

A reassessment of Table 4 demonstrates the extensive range of applications associated with mineral resources, illustrating how industrialization can generate a diverse array of products, goods, and services that contribute to national development. Mastery of the entire value chain of Strategic Minerals, Critical Minerals, and Rare Earth Elements would strengthen industries such as aerospace, aviation, automotive manufacturing, pharmaceuticals, defense, electronics, and agribusiness, among others.

Each country, however, faces distinct challenges. In Brazil, one of the principal structural bottlenecks within the mineral value chain lies in the refining and industrial processing stages. Historically, the country has established itself as an exporter of raw or minimally processed mineral commodities, while maintaining limited capacity for productive vertical integration. As a result, a substantial portion of value-added activities remains concentrated in other economies. This limitation reduces the competitiveness of the sector, which continues to depend on imports of manufactured products derived from its own mineral resources (CEBRI, 2025; Mancini, 2026).

Consequently, despite its vast natural resource endowment, Brazil faces significant challenges in advancing the processing of critical minerals, primarily due to technological constraints and the dominance of established global value chains controlled by other countries (Brazil, 2025). One of the most pressing examples concerns the vertical integration of the Rare Earth Elements production chain. To illustrate, Brazil still relies on imports of Rare Earth Oxides, which limits its ability to achieve full control over the corresponding value chain (Silva, 2025).

Nevertheless, there are promising prospects for medium- and long-term competitive advantages. The Brazilian mining sector plays a strategic role in both the national and global economy, not only because of the volume of exported mineral commodities but also because of its significant potential for producing critical minerals that are essential to the energy transition and the digitalization of economic activities (IBRAM, 2025).

This potential is supported by analyses of supply and demand dynamics for Strategic and Critical Minerals, which indicate that Brazil possesses substantial geological resources and considerable opportunities for integrating mineral and industrial policies. Minerals such as copper, graphite, lithium, nickel, and cobalt demonstrate reserve levels that significantly exceed projected domestic demand through 2050. Particularly noteworthy is nickel, whose reserves are estimated to be 128 times greater than cumulative projected demand, while copper and graphite reserves are estimated at 19 and 43 times projected demand, respectively. Converting this potential into industrial production would enable Brazil to secure supplies for strategic sectors while simultaneously positioning itself as a major supplier to global mineral markets, whose demand could increase fourfold by 2040 according to projections from the International Energy Agency (CEBRI, 2025).

Once again, it becomes evident that Industry 4.0 is leaving a lasting impact on the mining sector, transforming the ways in which minerals are extracted, processed, industrialized, and utilized. As technological progress continues, the mining industry is expected to evolve toward a future characterized by greater efficiency, safety, and sustainability (Reis, 2024).

Finally, in 1986, the United Nations General Assembly adopted Resolution 41/128, establishing the Declaration on the Right to Development, which affirmed that the socioeconomic development of a nation includes, among its fundamental principles, the exercise of full sovereignty over its wealth and natural resources (UN, 1986).

Nearly four decades later, this Declaration remains highly relevant. More than ever, it reflects the contemporary reality by reaffirming that mineral resources and their industrialization function as catalysts for progress, contributing to improvements in the overall quality of life of populations. From the extraction of mineral resources within the Earth's crust to their refinement and beneficiation, these processes enable value chains to generate advanced technological products, goods, and services designed to meet the evolving demands of modern societies.

#### **IV. Final Considerations**

Historically, the economic development of numerous countries has been influenced by the availability, extraction, and commercialization of mineral resources. Gold, silver, and iron are notable examples of minerals extracted from the Earth's subsurface that played a central role in different periods of economic prosperity across various nations.

With the advancement of scientific research, the development of new materials, and the adoption of disruptive technologies, additional elements of the periodic table began to be exploited for a wide range of applications, expanding their utilization in support of the scientific and technological progress achieved by humanity.

The energy transition, which is essential for mitigating the effects of global warming and climate change, would not have been possible without the production of high-value-added components composed of minerals possessing highly specific physicochemical characteristics.

The discovery of the numerous applications, capabilities, and properties of Strategic and Critical Minerals enabled the global scientific community to develop materials and equipment that have transformed the Contemporary Era. Owing to their high added value and disruptive technological potential, countries increasingly recognized the economic and technological importance of these mineral resources, concluding that the industrialization of Strategic and Critical Minerals would become a strategic driver of economic development. In this context, the Fourth Industrial Revolution (Industry 4.0) emerged, reshaping economic structures and accelerating scientific and technological advancement.

Accordingly, the objective of this study was to analyze how the mining and industrialization of Strategic and Critical Minerals act as catalysts for economic development in the twenty-first century. Based on this analysis, the study sought to provide insights for the academic community and for political, economic, scientific, and technological institutions, fostering greater awareness of and prioritization for the sustainable strengthening of these minerals' production chains in support of national development.

The findings indicate that the research successfully achieved its objectives by providing a comprehensive understanding of the factors that have led countries to recognize Strategic and Critical Minerals as indispensable to economic and technological development. Consequently, ensuring their industrialization and incorporation into the manufacture of electric vehicles, wind turbines, rechargeable batteries, defense systems, aerospace technologies, and numerous other advanced products represents a fundamental pathway toward national development.

The study also demonstrated the close interrelationship between climate change, renewable energy, and clean technologies associated with the energy transition, global warming mitigation, and economic decarbonization, all of which depend substantially on the industrialization and utilization of Strategic Minerals, Critical Minerals, and Rare Earth Elements.

The qualitative approach, supported by a literature review and documentary analysis, proved essential in demonstrating the extent to which the beginning of the twenty-first century has been characterized by a strong dependence on these natural resources. Their extraction, processing, and integration into comprehensive value chains possess the potential to transform the economic, environmental, energy, digital, and defense profiles of countries capable of utilizing them strategically and effectively.

Finally, future studies should consider examining the relationship between the exploration of Strategic and Critical Minerals and sustainable development, particularly the environmental impacts associated with the extraction, separation, beneficiation, refining, and industrialization of these resources. Further research should also investigate Brazil's participation, potential, current position, and future prospects as both a producer and consumer of Strategic and Critical Minerals within the global context.

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