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Geology, global distribution and significance of critical minerals: A comprehensive review

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ABSTRACT
Critical minerals play an important role in low-carbon technologies, national security, and advanced manufacturing, which has renewed global concern regarding their sustainable supply chains. A comprehensive review of peer-reviewed articles, geological survey documents, and international databases was compiled and integrated existing information on critical minerals is provided in this article. This review synthesizes recent advances in understanding the geological formation processes, global production patterns, and technological relevance of key critical minerals, including lithium, cobalt, nickel, graphite, rare earth elements, and platinum group minerals. The review highlights how geological settings such as carbonatites, laterites, pegmatites, and sedimentary basins control ore formation and enrichment. Current production remains highly geographically concentrated, creating strategic vulnerabilities and exposing supply chains to market volatility and geopolitical risk. The growing demand from electric vehicles, renewable energy systems, and digital infrastructure underscores the need for diversified exploration, innovation in mineral processing, and circular economy strategies. Overall, this review provides a framework to support resource planning, policy decisions, and future exploration strategies in the context of rapid global energy transition.

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1. INTRODUCTION

Critical minerals (CMs) are a subset of minerals (metals and non-metals), which are important for the functioning of modern technologies, for national security, and are vulnerable to supply chain disruptions (Calderon et al., 2020; Han et al., 2023). The definition of whether a mineral is considered to be critical or not is somewhat flexible, since this classification depends on not only the context and the stakeholder's point of view, but is also subject to change over time because the current techno-socio-economic paradigm largely defines the criticality level of minerals (Chakhmouradian and Wall, 2012). The criticality of a mineral is generally assessed based on its economic importance and the likelihood of disruptions in its supply chain (Schrijvers et al., 2020). These resources, mainly metals, have become the backbone of various twenty-first-century industries including electronics, telecommunications, renewable energy, and transportation, making their consistent supply key for societal advancement (Watari, 2020). For example, rare earth elements (REEs) are required for the production of permanent magnets used in wind turbines, while electricity networks need vast amounts of copper and aluminum (Groves et al., 2025). CMs are classified as battery elements (lithium, nickel, cobalt, manganese and graphite), rare earth elements and platinum groups of minerals (Deberdt et al., 2025). At the forefront of reducing carbon emissions and mitigating the effects of climate change are electric and hybrid vehicles, photovoltaic cells, wind turbines, batteries, and efficient lighting. These technologies are driving a growing global demand for energy-related critical minerals (IEA, 2023; Deberdt et al., 2025; Watari, 2020). From 1700 to the 2000s, energy technologies have evolved dramatically, alongside a steady rise in the number of elements used in these systems (Deberdt et al., 2025) (Fig. 1). Early technologies like the steam engine (1800s) relied on only a few basic materials. By the early 1900s, the advent of the combustion engine introduced greater material diversity.

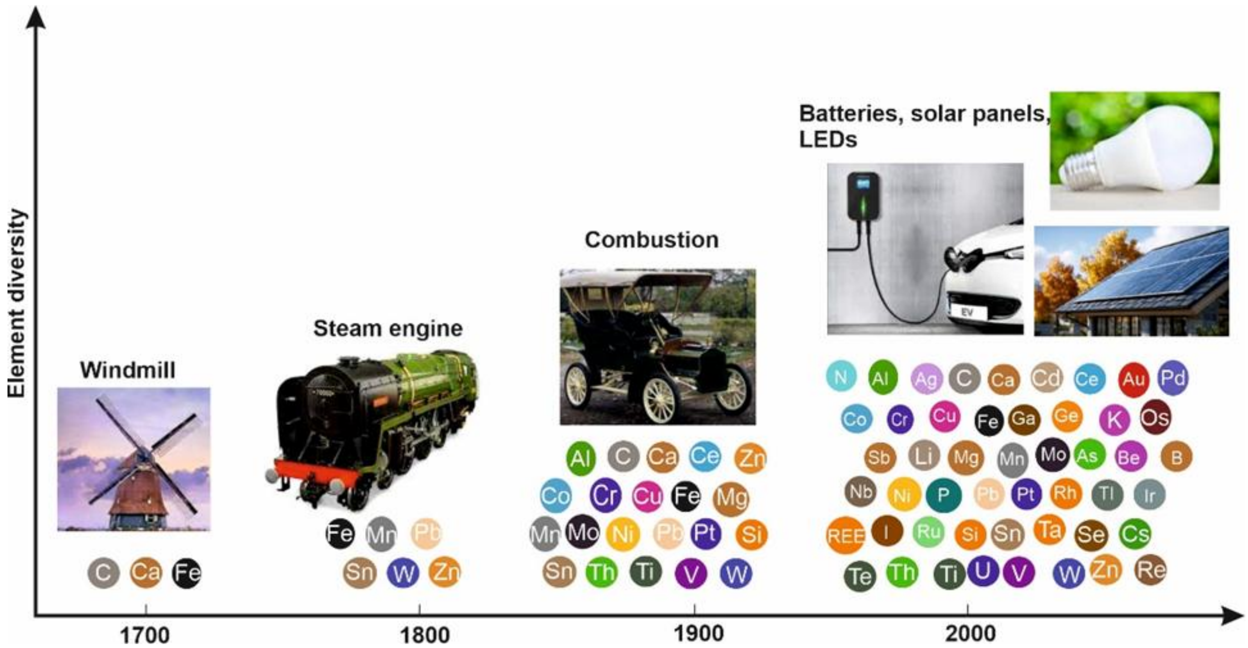

Figure 1. Temporal trends from 1700 to 2000s in energy technology development and growing variety of elements (along y-axis). The main shifts include the steam engine in the 1800s, the combustion engine around 1900 and the ongoing green energy transition since 2000s. The increasing element count reflects the growing complexity and material diversity of modern energy systems. The colored circles are used for illustrative purposes only. Abbreviations: REEs-Rare earth elements (modified after Achzet et al., 2011).

Table 1. Critical minerals list of different countries (Data taken from Deberdt et al., 2025). Abbreviations: N/A-Not available.

Country	Year of first publication (number of minerals)	Year of last update (number of minerals)
Australia	2019 (6)	2024 (31)
Brazil	2021 (20)	N/A
Canada	2021 (31)	2024 (34)
China	2016 (22)	N/A
European Union	2010 (14)	2023 (34)
France	2021 (24)	N/A
Germany	2014 (24)	2023 (23)
India	2023 (24)	N/A
Indonesia	2023 (47)	N/A
Japan	2006 (11)	2024 (36)
New Zealand	2025 (37)	N/A
South Africa	2022 (14)	N/A
South Korea	2023 (33)	N/A
Turkey	2025 (37)	N/A
United Kingdom	2021 (18)	2024 (33)
United States	2018 (35)	2022 (50)

Since the 2000s, the green energy transition—driven by solar, wind, batteries, and electric mobility—has accelerated the use of many more elements, especially critical minerals. As energy systems have become more advanced, their material requirements have grown more complex. Modern technologies now depend heavily on critical minerals such as lithium, cobalt, rare earth elements, nickel, and graphite, reflecting the increasing technological sophistication and material intensity of clean energy solutions. They are also vital to power the global transition to a low carbon emissions economy, and the renewable energy technologies that will be required to meet the 'Net Zero' commitments of an increasing number of countries around the world (IEA, 2023). Based on their specific needs and priorities, individual countries have identified varying numbers of critical minerals (Deberdt et al., 2025) (Table 1). The increasing demand for CMs indicates a lack of an integrated approach about the geological controls link with resource potential and sustainable supply strategies. Currently, research work on CMs is not consolidated, showing limited integration in metallogenic processes, resource evaluation, supply-chain risks, recycling potential and Environmental, Social, and Governance (ESG) constraints. Consequently, it has become essential to identify and develop strategic value chains for the minerals which are critical to country. In this article, the CMs are given into three categories based on their usage: (i) battery elements, (ii) platinum group of minerals and (iii) rare earth elements. It includes a compilation of geological processes, global distribution, and usage of CMs to foster strategic resource planning and guiding future exploration strategies to meet the rapidly growing demand of global energy transition.

2. USAGE AND GLOBAL DISTRIBUTION OF CRITICAL MINERALS

Based on the usage, the critical minerals are mainly divided into three types such as battery minerals, platinum group minerals (PGMs), and rare earth elements (REEs) (Deberdt et al., 2025). These minerals are discussed below:

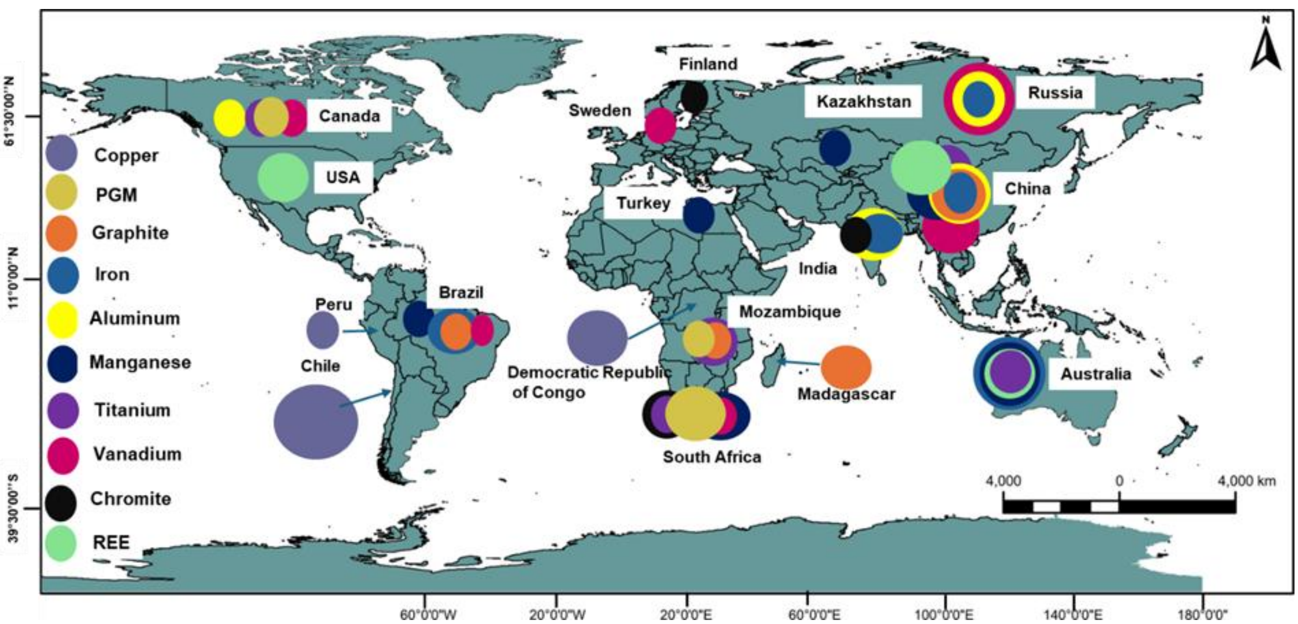

Figure 2. Global distribution of critical minerals (modified after Müller et al., 2025).

2.1 Battery minerals

Battery types of minerals include cobalt, copper, graphite, lithium, manganese, and nickel. They are mostly driven by their critical role in battery manufacturing for EVs, portable electronics, and other systems that rely on energy storage (Groves et al., 2023). For example, 71 % of cobalt production is currently utilized in battery manufacturing, and it represents 93 % of demand growth in 2023. In 2024, approximately 76 % of the world's cobalt supply was mined in the Democratic Republic of the Congo (DRC), followed by Indonesia (10 %), and 78 % of it is refined in China. In addition, copper mining is primarily distributed in Chile (23%), the DRC (14%), and Peru (11%), which together dominated global production in 2024 (Fig. 2, 3) (Groves et al., 2025). Natural graphite is used in battery anodes, and its production is concentrated in China (79 %), followed by Madagascar (6 %) and Mozambique (5 %). Lithium is primarily extracted from pegmatite deposits in Australia (37 %), which includes Chile (20 %) and Argentina (8 %) achieve commercial-scale production (Balaram et al., 2024). Finally, nickel is used in battery cathodes and various high-strength alloys, and nickel mining is dominated by Indonesia (59 %), followed by the Philippines (9 %), other countries (8 %), Russia (6 %) and Canada (5 %).

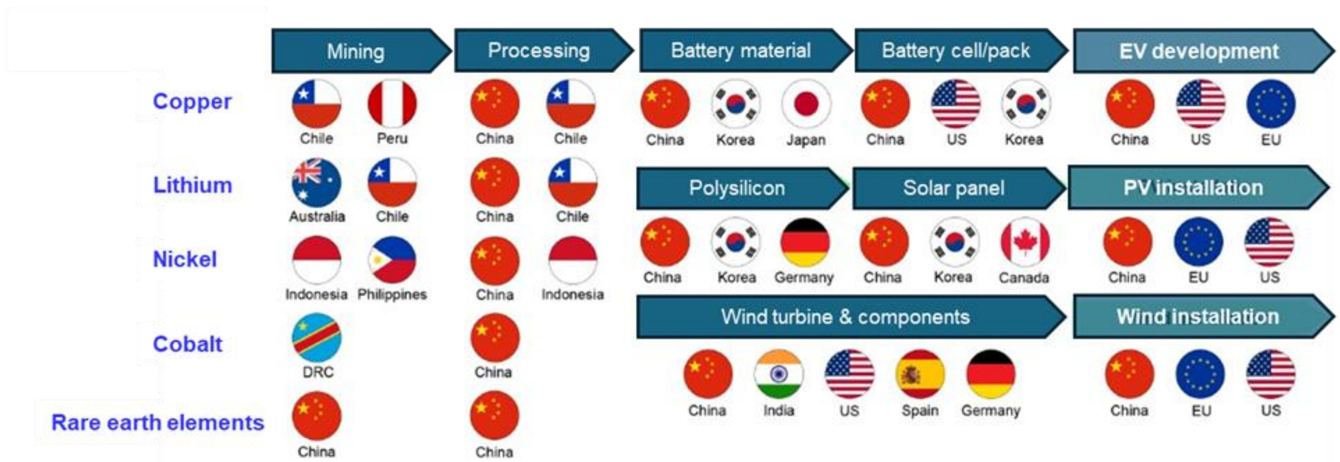

Figure 3. Supply chains of selected critical minerals in clean energy technologies (adapted from IEA, 2023). Abbreviations: DRC = Democratic Republic of the Congo; EU = European Union; US = United States; Russia = Russian Federation; China = People's Republic of China.

2.2. Platinum group minerals (PGMs)

These types of minerals are a collection of six elements – platinum, palladium, rhodium, ruthenium, iridium, and osmium due to their similar physical and chemical properties, including exceptional catalytic capabilities and high resistance to corrosion (Reich and Simon, 2025). These elements are among the rarest globally and are important raw materials for catalysts used in chemical manufacturing, automotive catalytic converters, and petroleum refining (Sittner et al., 2022). Although they are not directly linked to battery technologies, PGMs play a crucial role in hydrogen production, such as corrosion resistant electrolyzes which split water into hydrogen and oxygen. They are also key components in the fuel cells which enable fuel cell electric vehicles (FCEVs) and other hydrogen energy systems. Platinum group minerals mining is highly concentrated in a few regions. Platinum mining is similarly dominated by South Africa, accounting for 71 % of global output, with additional contributions from Zimbabwe (11 %), Russia (11 %), and Canada (3 %; Fig. 2).

2.3 Rare earth elements (REEs)

REEs are usually divided between heavy (HREEs) and light (LREEs) and are primarily used to produce the high-performance permanent magnets that enable the compact efficient motor/generators in wind turbines, EVs, and similar energy efficient technologies (Müller et al., 2025). By value, rare earth permanent magnets (REPMs) make up about 78% of the REE industry. Phosphors for lighting and displays, specialized detectors, metallurgical alloys, and some battery technologies that rely on the qualities of REEs are some other significant uses. Finally, some REEs are used in low value applications as catalysts and polishing agents. Both types of REEs have been extensively mined in China over the past 20 years, making up 69 % of global production (Figs. 2, 3). Other key producers include the U.S. (12 %), Myanmar (8 %), Australia (3 %), Nigeria (3 %), and Thailand (3 %).

3. GEOLOGICAL SETTINGS

Globally, critical minerals can be found in a wide range of geological conditions such as weathering, hydrothermal, sedimentary, and magmatic processes (Schulz et al., 2017). The primary hosts of REEs include heavy-mineral placers rich in monazite and xenotime, carbonatite–alkaline complexes, and ion-adsorption clays created by deep tropical weathering of granites (Wu et al., 2023). Lithium is frequently found in lithium-rich claystones, continental evaporitic brines, and pegmatites containing spodumene (Balaram et al., 2024). Cobalt is commonly found in magmatic Ni–Cu sulfide systems, lateritic profiles formed over ultramafic rocks, and sediment-hosted Cu–Co deposits (Yang et al., 2023). In tropical regions, nickel is mainly found in laterite deposits that were created by severe weathering and magmatic sulfide deposits. High-grade metamorphic terrains contain flake graphite, hydrothermal veins, and amorphous graphite from metamorphosed coal seams. PGMs can be found in magmatic Ni–Cu sulfide deposits and layered mafic–ultramafic intrusions like the Bushveld Complex (Sittner et al., 2022). Greisen, skarn, vein-type deposits, and placers in Southeast Asia are examples of granite-related hydrothermal systems that are closely linked to tungsten and tin. Vanadium is found in sandstone-hosted uranium-vanadium deposits, organic-rich shales, and vanadiferous titano-magnetite layers within mafic intrusions. While titanium (ilmenite and rutile) is prevalent in heavy-mineral placer deposits and Fe–Ti oxide layers of mafic intrusions, beryllium is primarily found in pegmatites and volcanic tuffs. In general, deep-seated magmatic processes, surface weathering, sedimentary transport, and reworking in both marine and continental contexts all contribute to the global distribution of essential minerals.

4. MINING, PROCESSING AND EXTRACTION TECHNIQUES

Depending on the location and type of minerals, several techniques are used for their mining and processing. Open-pit or underground mining is typically used to extract hard-rock deposits, such as lithium pegmatites, rare-earth carbonatites, nickel–copper sulfides, and tin–tungsten veins (Fikru and Romani, 2025). After the ore is crushed and pulverized, basic physical methods such as flotation, gravity separation, or magnetic separation are used to separate the valuable minerals (Raju, 2020). The salty water in lithium brines is piped to the surface, where it is either treated using modern direct-extraction technologies that use chemical filters to separate lithium or left to evaporate in huge ponds (Balaram et al., 2024; Hormozzade Ghalati et al., 2025). High-temperature or acid-leaching techniques are used to recover nickel and cobalt from laterite soils, while gravity, magnetic, and electrostatic separation are used to improve heavy-mineral sands that contain ilmenite, rutile, or monazite (Yang et al., 2023). To separate each rare-earth element, more intricate chemical processing is required, such as solvent extraction and acid treatment. Platinum group metals are recovered by smelting and refining sulfide concentrations (Sittner et al., 2022), while graphite is primarily concentrated by flotation. To produce important minerals that are pure enough for batteries, electronics, and high-tech applications, a combination of mining, physical beneficiation, and chemical processing is typically needed.

5. SUSTAINABLE SUPPLY

Critical minerals are mainly affected by interconnected geopolitical, circular economy, and sustainability challenges due to their vital role in clean energy technologies, advanced manufacturing, and strategic industries. The heterogeneous distribution of critical mineral resources can potentially lead to geopolitical supply risks, or even depletion soon (Fig. 3). Geopolitically, supply-chain vulnerabilities, strategic competition, and dependency on just a few producing countries have all been driven by the highly unequal global distribution of critical mineral resources and processing capacities, raising concerns about resource security and possible supply disruptions (Fig. 3). In contrast to the strong demand for these minerals, their supply is highly volatile. Many deposits are in developing and highly underdeveloped countries, where mining has historically had challenges with technological limitations, corruption, pollution and human rights. From a perspective of the circular economy, measures to reduce dependency on primary mining are limited by poor recycling rates, technological constraints in material recovery, and insufficient secondary supply. The environmental, social, and governance (ESG) effects of extraction and processing, including land disturbance, water use, emissions, and social dangers, present additional sustainability difficulties. To achieve a secure and sustainable critical mineral supply, an integrated strategy requires that can integrate supply-chain diversity, ethical sourcing, technological advancements in recycling and recovery, and strong political and regulatory frameworks.

6. SUMMARY AND CONCLUSIONS

Critical minerals are essential for developing renewable energy systems, boosting important sectors, and driving technological innovation. Geological processes significantly control the mode of occurrence, and their unequal global distribution poses serious supply-chain vulnerabilities. Future research on critical minerals should be meticulously aligned with strong global policies such as the European Union Critical Raw Materials Act (EU CRM) and the US Critical materials strategy to promote evidence-based implementation of policies. Furthermore, the research should also be concentrated on developing more effective recycling technologies, better refining processes, and cleaner extraction techniques. To evaluate the mining, recycling, and replacement methods with achieving sustainability and ESG guidelines, environmental and socioeconomic studies are required. Analyses of supply and demand as well as geopolitical risk are crucial to evaluating domestic production, processing, recycling and supply chain goals.

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