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Mineralogy and Geochemistry of Critical Minerals: Exploration, Extraction, and Sustainability

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ABSTRACT

Critical minerals, such as rare earth elements (REEs), lithium, and cobalt, are essential for modern technologies, including renewable energy, electronics, and advanced manufacturing. The increasing demand for these minerals has led to a surge in exploration and extraction efforts. However, their mineralogy and geochemistry are not well understood, hindering sustainable extraction and supply chain management. This review examines the current state of knowledge on the mineralogy and geochemistry of critical minerals, highlighting exploration, extraction, and sustainability challenges. Research has identified new mineral deposits and improved understanding of critical mineral geochemistry. Ion adsorption clay deposits and pegmatites are significant sources of REEs, while lithium is often extracted from brines and hard rock deposits. Cobalt is commonly associated with copper and nickel deposits. Advanced analytical techniques, such as machine learning and spectroscopy, are enhancing exploration and extraction efficiency. However, environmental concerns, such as water pollution and land degradation, accompany extraction activities. Sustainable practices, like recycling and urban mining, are being explored to mitigate these impacts. The mineralogy and geochemistry of critical minerals are complex and not yet fully understood. While advances in exploration and extraction technologies are improving supply chain resilience, sustainability remains a pressing concern. Future research should focus on developing eco-friendly extraction methods, improving recycling rates, and promoting responsible sourcing practices to ensure the long-term availability of these critical minerals.

Keywords: *Critical Minerals, Extraction, Rare earth elements, Sustainability, and Recycling rate.*

Introduction

The global push toward decarbonization and digital transformation has intensified demand for critical minerals such as lithium, cobalt, rare earth elements, and graphite [1]. These minerals are indispensable to the production of electric vehicle batteries, wind turbines, solar panels, and semiconductors, making them strategic assets for countries aiming to lead in clean energy and advanced manufacturing [2].
Beyond energy, critical minerals underpin national security and defense systems, including missile guidance, satellite communications, and stealth technologies. As a result, governments are increasingly treating these resources as vital to economic resilience and geopolitical stability [3]. The United States, European Union, and China have all released critical mineral strategies to secure supply chains and reduce dependency on foreign sources [4].

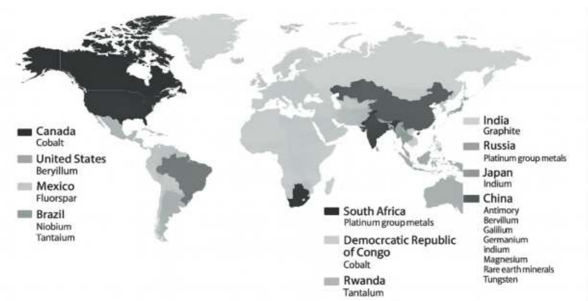

Figure. 1. Global distribution of major critical mineral deposits
***Source**: [5]*

Geologically, these minerals are unevenly distributed and often concentrated in politically sensitive or environmentally fragile regions. Figure 1 shows the production concentration of critical mineral materials, highlighting how Europe is heavily dependent on other continents. For example, cobalt is primarily sourced from the Democratic Republic of Congo and Canada; rare earths and graphite from China; and platinum group metals from South Africa and Russia. This geographic concentration creates vulnerabilities in global supply chains and raises concerns about sustainability, labor practices, and environmental degradation [6].

Mining and processing of critical minerals can lead to deforestation, water pollution, and social displacement, especially in regions with weak governance. These impacts have prompted calls for sustainable extraction practices, including improved waste management, reduced energy use, and community engagement [7]. Moreover, the concept of a circular economywhere minerals are recycled and recovered from end-of-life products, is gaining traction as a way to reduce primary extraction and environmental harm. Table 1 summarizes key critical minerals, their industrial applications, and major supplying countries based on recent MDPI and NCBI sources.

Table 1. Selected critical minerals, use, and supplying countries

Mineral	Key Uses	Major Suppliers
Lithium	Batteries (EVs, grid storage)	Australia, Chile, China
Cobalt	Rechargeable batteries, alloys	DRC, Canada, Russia
Rare Earths	Magnets, wind turbines, electronics	China, USA, Myanmar
Nickel	Stainless steel, batteries	Indonesia, Philippines, Russia
Graphite	Battery anodes, lubricants	China, Mozambique, India
Platinum Group	Catalysts, electronics, fuel cells	South Africa, Russia, Zimbabwe
Tungsten	Aerospace, electronics, defense	China, Vietnam, Russia

Sources: *[8]*

This study aimed to explore the mineralogical and geochemical characteristics of critical minerals, assess current extraction technologies, and evaluate sustainability frameworks. By integrating geological science with policy and environmental ethics, it seeks to inform responsible resource management and support a resilient, low-carbon future.

Mineralogy of Critical Minerals

The industrial significance and extraction complexity of important minerals are supported by their mineralogical properties. These minerals frequently have peculiar crystal chemistry, are found in geologically uncommon settings, and develop under specific geochemical conditions. Their unique atomic configurations and bonding characteristics that allow for high conductivity, magnetism, or catalytic action are just as valuable as their rarity [9].

Crystal Chemistry and Mineral Groups

Each of the several mineral groups that make up critical minerals has unique bonding mechanisms and crystal shapes. Typically found as oxides (such as monazite and bastnäsite), rare earth elements (REEs) are distinguished by their complicated coordination environments and huge ionic radii. Their f-electron configurations contribute to luminous and magnetic properties, which are crucial for renewable technologies and electronics [10].

Lithium ions occupy interstitial positions in layered silicate structures found in pegmatites that contain lithium, such as spodumene and lepidolite. Compared to lithium brines, these minerals are valued for their high lithium concentration and ease of processing. Because of their varied oxidation states and associations with iron and magnesium, cobalt sulfides (like carrollite) and nickel laterites (like garnierite) provide extraction issues. Leaching behavior and metallurgical recovery are influenced by their crystal chemistry [11].

Mineral Occurrence and Environments of Host Rock

Different geological settings are home to critical minerals, which act as indicators for exploration. Coarse-grained igneous rocks rich in incompatible elements, including tantalum, niobium, and lithium are known as pegmatites. The main sources of REEs and niobium are carbonatites, which are uncommon igneous rocks rich in carbonate. Nickel and cobalt are found in ultramafic rocks and laterites, which are frequently created by severe tropical weathering [12]. Brines are important suppliers of boron and lithium, especially in closed-basin salt flats. Geological markers, including alteration halos, geochemical anomalies, and structural controls, are used to identify these settings [13].

Mineral Associations and Alteration Patterns

Metasomatism, a process involving chemical exchange between fluids and host rocks, can significantly modify mineral chemistry. In carbonatite systems, metasomatic alteration often enhances concentrations of rare earth elements (REEs), forming enriched zones that are more economically viable.

Similarly, weathering in tropical environments leads to the development of lateritic profiles, where elements like nickel and cobalt become concentrated near the surface due to leaching and residual enrichment [14].

Hydrothermal alteration, common in geothermal and tectonically active regions, mobilizes lithium and other rare metals. These fluids precipitate secondary mineral phases such as pectolite, monazite, and ferroan silicates, which vary in grain size and purity. These variations directly impact metallurgical behavior, requiring tailored extraction techniques to optimize recovery and minimize waste [15].

Figure 2 displays thin-section photomicrographs of selected critical minerals under plane-polarized light (PPL) and back-scattered electron (BSE) imaging. The images reveal diverse mineral textures and associations, including quartz (Qtz), alkali feldspar (Afs), pectolite (Pcl), monazite (Mnz), aeschynite (Aes), and ferroan phases (Fer). These photomicrographs illustrate how alteration processes shape mineral assemblages and influence ore characteristics across different deposit types.

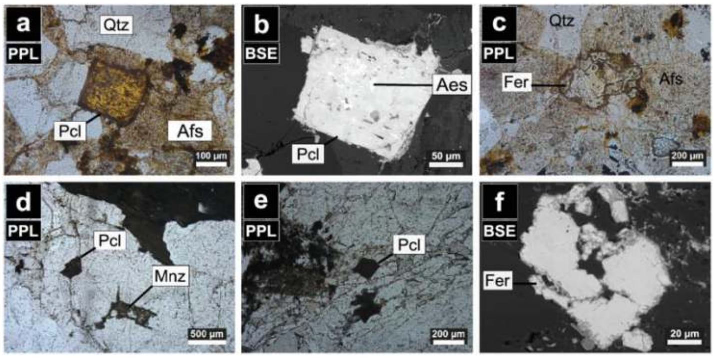

Figure 2. Thin-section photomicrographs of selected critical minerals
Source: *[16].*

Adapted from *Zircon revels multistage, magnetic, and hydrothermal rare earth element mineralization at Desert Lake, Nova Scotia, Canada.*

Geochemistry of Critical Minerals

Finding feasible deposits, evaluating ore grade, and creating effective extraction techniques all depend on an understanding of the geochemistry of important minerals. These minerals frequently exhibit distinctive elemental tendencies, originate under specific geological settings, and have unique isotopic signatures that can be used to track their evolutionary history [17]. Incompatible elements, which are difficult to fit into ordinary rock-forming minerals during crystallization, are frequently linked to critical minerals. Geochemically different elements include lithium, niobium, and rare earth elements (REEs), which tend to concentrate in residual melts or fluids. On the other hand, suitable elements like iron and magnesium are less concentrated in late-stage processes and are easily integrated into early-forming minerals [18].

The relative abundance of light (LREE) and heavy (HREE) rare earths is shown by REE patterns, which are frequently displayed using spider diagrams. Geologists can differentiate between magmatic, hydrothermal, and supergene origins using these patterns as geochemical fingerprints. For instance, enriched HREEs indicate carbonatite or alkaline igneous origins, whereas negative europium anomalies usually indicate plagioclase fractionation [19].

Formation Processes
Numerous geochemical processes result in the formation of critical mineral deposits:
i. Magmatic fractionation creates pegmatites rich in tantalum, niobium, and lithium by concentrating incompatible elements in late-stage melts.

ii. Supergene weathering increases surface concentrations of nickel and cobalt by leaching and redeposition in tropical lateritic environments; hydrothermal enrichment mobilizes metals such as cobalt, REEs, and tungsten through hot, mineral-rich fluids that precipitate in fractures and faults.

iii. Ore grade and metallurgical behavior are impacted by these processes, which change mineralogy and chemistry [20, 21, 22].

Isotope Geochemistry
Radiogenic isotopes such as U-Pb, Sm-Nd, and Rb-Sr are widely used in age dating to constrain the timing of mineralization events. For example, U-Pb dating of monazite and zircon is instrumental in identifying the formation age of REE-bearing pegmatites, helping geologists understand the tectonic and magmatic history of mineral-rich regions [23].
In parallel, stable isotopes including $\delta^{18}O$, δD, and $\delta^{13}C$ are used to trace fluid sources and alteration processes. These isotopes reveal whether mineralizing fluids originated from meteoric, metamorphic, or magmatic sources, and help reconstruct the thermal and chemical evolution of ore systems. For instance, $\delta^{18}O$ and δD values can distinguish between surface-derived and deep-seated fluids, while $\delta^{13}C$ is often used in carbonatite systems to infer mantle versus crustal contributions [24].
Figure 3 shows spider diagrams comparing the primitive mantle-normalized concentrations of trace elements, including REEs, across different deposit types. The diagram highlights distinct geochemical patterns between Archean basalts and modern mid-ocean ridge basalts (MORB), illustrating how REE distribution varies with geological setting. Archean basalts exhibit elevated Rb and Ba and depleted Nb, while MORB samples show more consistent enrichment in REEs, reflecting differences in mantle source and magmatic evolution.

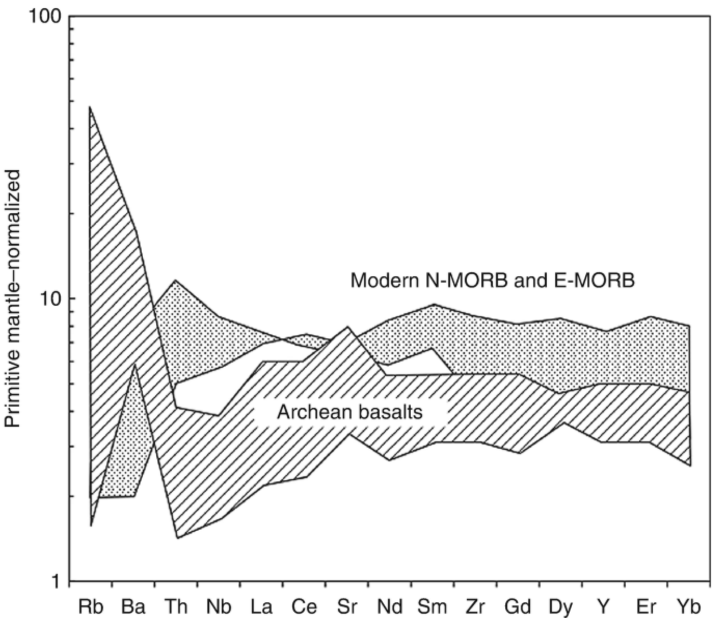

Figure 3. Spider diagrams showing rare-earth element patterns Exploration
Source: *[25]*

Adapted *from Trace Element Contents of Mantle-Derived Magmas Through Time.*

Techniques for Critical Minerals
A multidisciplinary strategy combining field geology, geophysics, geochemistry, and remote sensing is necessary to locate significant mineral resources. Exploration techniques have changed to increase precision, lower prices, and lessen ecological disturbance as demand for minerals like lithium, cobalt, and rare earths rises. Conventional field techniques continue to be fundamental. Finding advantageous lithologies and tectonic environments where mineralization is likely is made easier by geological mapping and structural research. For instance, pegmatites that contain lithium are frequently found near granitic contacts or shear zones. During field surveys, indicator minerals like spodumene (lithium), garnierite (nickel), and monazite (REEs) provide visual cues. The chemical examination of host rocks, or lithogeochemistry, directs sampling techniques and aids in the detection of minute irregularities [26].

Geophysical Exploration
Each technique has advantages and disadvantages. Magnetic surveys are useful for identifying ultramafic rocks rich in nickel and cobalt; radiometric techniques detect radioactive elements like thorium and uranium, which are frequently associated with REE-bearing minerals; gravity surveys reveal dense bodies like carbonatites; and electromagnetic (EM) methods detect conductive sulfide zones. However, magnetic surveys are quick and in areas with complex geology [15].

Geochemical sampling
In order to identify elemental anomalies, geochemical sampling entails gathering and examining soil, stream sediments, and drill cores [1]. Pathfinder elements, such as arsenic, antimony, and barium, frequently accompany critical minerals and aid in defining mineralized zones. Statistical analysis and spatial modeling are necessary for anomaly interpretation in order to separate genuine signals from background noise. Sampling grids and multi-element assays are used to refine targets prior to drilling [2].

Remote Sensing and AI-Assisted Exploration
Machine learning and remote sensing are becoming more and more important in modern exploration. Using sensors mounted on drones or satellites, hyperspectral imaging records mineralogical information at hundreds of wavelengths. This method can map lithology, find surface manifestations of mineralization, and locate alteration zones. AI systems, such as convolutional neural networks and random forests, use multisource data to anticipate deposit locations and categorize different types of minerals. These instruments improve productivity and lessen human interpretation bias [3, 4].

Mining Techniques
Critical minerals, including nickel, lithium, cobalt, and rare earth elements (REEs) are extracted and processed using intricate, multi-stage processes. These strategies must strike a balance between environmental sustainability and economic efficiency, particularly as demand for clean energy technologies rises. For hard-rock minerals, open-pit and underground mining are the main methods. For shallow, laterally widespread ore complexes such as nickel sulfides and pegmatites that contain lithium, open-pit mining is preferred.

Although it greatly disturbs the land, it offers excellent productivity. Deeper resources, such as cobalt-rich areas in the Democratic Republic of the Congo, are mined underground, which is less disruptive but more expensive [3]. In-situ leaching, particularly for lithium brines in salt flats of Chile and Argentina, involves injecting fluids to dissolve lithium salts underground and pumping them to the surface. This method reduces surface impact but raises concerns about water use and aquifer contamination [4].

Mineral Processing

Ores are crushed and ground after mining to release valuable minerals. For REEs, cobalt, and nickel, froth flotation is a popular method that uses variations in surface chemistry to separate minerals. For dense minerals like tantalum and niobium, gravity separation works well, particularly in pegmatitic ores. These procedures are specific to the mineralogy and texture of the ore, necessitating exact control to maximize recovery [5]

Refining and Separation Technologies

Ion exchange and solvent extraction are important refining techniques for vital minerals. Ion exchange uses resin columns to separate ions according to size and charge, whereas solvent extraction uses organic solvents to selectively bind and separate target metals. Because of their comparable ionic radii and chemical behavior, REEs are extremely difficult to separate, necessitating multi-stage separation and exact pH control [6]. By increasing selectivity and lowering hazardous waste, recent developments in ionic liquid systems provide more environmentally friendly options. Scalability and cost, however, continue to be obstacles to broad adoption [7].

Energy and Environmental Cost of Extraction

Particularly during grinding, flotation, and high-temperature refinement, critical mineral extraction requires a lot of energy. There is a risk of contaminating soil and water when chemical reagents like hydrochloric acid, sulfuric acid, and organic solvents are used. Depending on the type of deposit and processing method, these procedures have different carbon footprints. For instance, brine lithium uses more water but has fewer emissions than hard-rock lithium [8]. The energy needs of the main extraction techniques are contrasted in Table 2.

Table 2. Energy requirements of major extraction methods

Method	Energy Use (kWh/ton)	Environmental Impact
Open-pit mining	100–300	High land use, dust, habitat loss
Underground mining	300–600	Lower surface impact, ventilation cost
In-situ leaching	50–150	Water-intensive, aquifer risk
Froth flotation	200–400	Chemical waste, tailings
Solvent extraction	400–800	Organic solvent disposal
Ion exchange	300–700	Resin regeneration, chemical use

Source: *[9]*

Environmental Impacts and Sustainability Challenges

Critical mineral mining's quick growth has raised awareness of its effects on society and the environment. These issues, which range from community displacement to acid mine drainage, emphasize the necessity of ethical behavior and circular economy approaches.

Acid mine drainage (AMD), which happens when sulfide minerals oxidize when exposed to air and water and produce sulfuric acid that leaches heavy metals into ecosystems, is one of the most urgent problems. AMD has been shown to cause long-term soil and river contamination in nickel and cobalt mines [10].

Another issue is heavy metal contamination, especially in areas with artisanal mining where processing uses arsenic and mercury. These contaminants bioaccumulate, endangering human health as well as biodiversity. Communities and ecosystems downstream are devastated when tailings dam failures, like those seen in South America, discharge enormous amounts of toxic slurry [11].

Water and Energy Challenges

Large amounts of water are needed to extract lithium from brines, frequently in dry areas like the Atacama Desert. As a result, local people and mining companies compete for limited water supplies [12]. In contrast, the use of chemical reagents and energy-intensive separation procedures in rare earth refining results in a large carbon impact. Compared to other metals, life cycle evaluations reveal that the production of REEs contributes disproportionately to greenhouse gas emissions [13].

Social and Ethical Concerns

Social and ethical issues are another characteristic of critical mineral supply chains. Large-scale mining operations have the potential to harm cultural heritage and livelihoods by uprooting communities. Concerns regarding child labor, hazardous working conditions, and a lack of regulation have been brought up by artisanal cobalt mining in the Democratic Republic of the Congo [14]. With programs like blockchain tracking and certification programs emerging to guarantee ethical sourcing, these problems highlight the need of supply chain transparency [15].

Waste Management and Circular Economy

Moving away from extraction and toward waste management and circular economy models is necessary for sustainability. Lithium, cobalt, and rare earths can be recovered through battery and electronics recycling, which lessens the need for initial mining. Recovering metals from electronic waste through urban mining is becoming more popular as a practical substitute. In order to match mineral production with environmental objectives, new zero-waste extraction models seek to reduce tailings and repurpose byproducts [16]. The sustainability metrics used to assess important mineral operations are shown in Table 3.

Table 3. Sustainability Indicators for critical mineral operations

Indicator	Measurement Focus	Example Application
Water Use	Volume consumed per ton of ore	Lithium brine extraction
Carbon Footprint	CO_2 emissions per kg of product	Rare earth refining
Waste Management	Tailings volume, recycling rates	Battery recycling plants
Social Responsibility	Community engagement, labor rights	Cobalt mining in DRC
Supply Chain Transparency	Traceability, certification	OECD due diligence guidelines

Source: *[17, 18]*

Emerging Technologies and Future Directions

As a low-energy substitute for conventional smelting, bioleaching the employment of bacteria to dissolve and mobilize metals, is becoming more popular. Compared to traditional methods, microorganisms like Acidithiobacillus ferrooxidans can oxidize sulfide minerals, releasing cobalt, nickel, and rare earths with lower greenhouse gas emissions [19].

Additionally, ionic liquids and green solvents are being developed to replace dangerous chemicals in mineral separation. These solvents reduce hazardous waste streams while providing excellent selectivity for lithium and rare earth elements. Their potential for recovering metals from tailings and recycling electronic trash has been shown by pilot investigations [20].

Artificial Intelligence and Automation

Exploration and processing are being revolutionized by artificial intelligence (AI). In order to more accurately identify mineralized zones, predictive mapping integrates geophysical, geochemical, and remote sensing data using machine learning algorithms. AI-powered models increase targeting effectiveness and lower exploration costs [21]. Automated sorting systems with robotics and sensors may separate ore from garbage in real time in processing facilities, increasing recovery rates and consuming less energy. When sorting complex deposits by hand is ineffective, these methods work especially well [22].

Nanotechnology Applications

New approaches to improved material recovery are provided by nanotechnology. Rare earth elements can be selectively extracted from diluted waste streams, such as industrial effluents and mining tailings, using nanostructured adsorbents. This strategy promotes circular economy models and enhances recovery [23]. Furthermore, nanoparticles are being designed to function as catalysts in leaching procedures, speeding up reactions and using less chemicals. These uses demonstrate how nanotechnology can improve mineral processing efficiency and sustainability.

Policy and Global Cooperation

International cooperation and policy frameworks are necessary to encourage technological advancements. Critical mineral supply chain regulations that prioritize ethical sourcing, recycling, and transparency are being adopted by governments more frequently. The U.S. Critical Minerals Strategy and the European Union's Critical Raw Materials Act are two examples of initiatives to ensure supplies while advancing sustainability [24].

Addressing common issues like artisanal mining, environmental degradation, and geopolitical risks requires international cooperation. Responsible practices and fair resource distribution are promoted by programs like the OECD Due Diligence Guidance and international research collaborations [25].

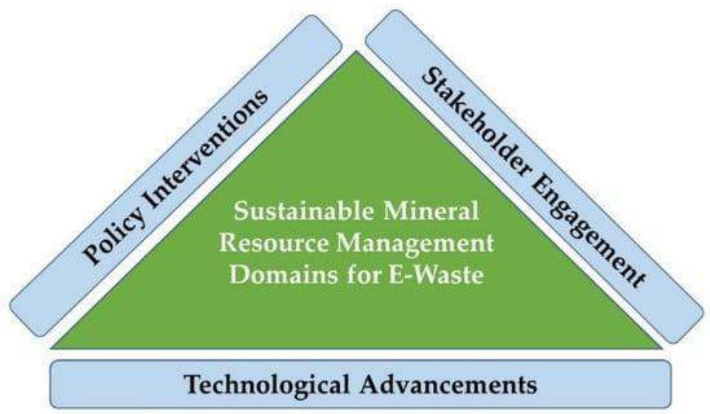

Figure 7. Future roadmap for sustainable critical mineral operation

Sources: [26]

***Adapted from** The Role of E-Waste in Sustainable Mineral Resource Management* A future roadmap for sustainable vital mineral operations that incorporates green technologies, artificial intelligence, nanotechnology, and policy frameworks is shown in Figure 4.

Conclusion

Although their extraction presents major geological, environmental, and social issues, critical minerals are essential to the shift to clean energy and modern technology. The exploration and extraction techniques that find and process them, as well as the mineralogical and geochemical insights that explain their rarity and value, have all been highlighted in this review.

The data emphasize how urgently sustainability standards, such as lower energy consumption, waste management, and ethical supplier chains, are needed. Going forward, balancing global demand with environmental stewardship will need coordinated efforts across geology, engineering, and policy. The vital mining industry may develop into a more robust and sustainable future by embracing new technology and encouraging global collaboration.

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