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Minerals: A Comprehensive Review of Classification, Properties, Formation, and Their Role in Modern Technology and Sustainability

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Abstract

Minerals are naturally occurring, inorganic, solid elements with a definite chemical composition and a characteristic crystal structure. They are the building blocks of rocks. Minerals are the key to the development and progress of human civilization. They are used for the development of infrastructure, electronic gadgets, agriculture, and medicine. This research paper aims to present an exhaustive overview on the field of mineralogy, which includes the definition, classification, physical and chemical properties, geological formation, geographical distribution, industrial uses, and environmental importance of minerals. Additionally, this paper will discuss the current scenario of mineral extraction and the rising need for critical minerals for the development of modern technology. With over 5,700 known mineral species discovered to date, this paper will present a summary on the current knowledge on these topics, which has been developed over decades of geological research. Lastly, this paper will present the future perspectives on mineralogy research, which includes nano mineralogy and the discovery of minerals on other planets.

Keywords: Minerals, mineralogy, crystallography, rock-forming minerals, ore deposits, silicates, crystal structure, geochemistry, critical minerals, industrial minerals

INTRODUCTION

Minerals form the very foundation of the Earth's crust and mantle. The branch of geology dealing with the study of minerals is called mineralogy, and it is as old as geology. The word 'mineral' itself has its roots in the Medieval Latin word 'minerale,' meaning something mined. From the dawn of civilization, humans have depended on minerals for their tools, weapons, adornments, colorants, and building materials. The Bronze Age, the Iron Age, and the Industrial Revolution were characterized by the ability of humans to exploit particular minerals and metals. Today, minerals play a crucial role in the sustenance of the present world. Silicon minerals form the backbone of the semiconductor industry, lithium and cobalt minerals form the power source of rechargeable batteries, rare earth minerals form the powerful magnets of wind turbines and electrical motors, and calcium phosphate minerals form the backbone of the world's agriculture through fertilizers. As the world shifts its focus to clean energy and electronic technology, the demand for particular minerals, or 'critical' minerals, has increased manifold, and the science of minerals becomes more and more relevant. This paper proposes to give a detailed academic overview of the subject of minerals, divided into six important themes [1].

The objective of this paper is to give a comprehensive academic overview of minerals under six main themes: (1) definition and classification, (2) physical and chemical properties,

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(3) formation and geological occurrence, (4) main groups of minerals, (5) economic and industrial applications, and (6) environmental and sustainability issues.

DEFINITION AND CLASSIFICATION OF MINERALS

Scientific Definition

The classical definition of a mineral states that it is "a naturally occurring, inorganic, solid element with a definite chemical composition and an ordered atomic structure [2]." The five criteria that are used to define what constitutes a mineral are:

- *Naturally occurring:* The minerals must occur in nature and not be man-made.
- *Inorganic:* The minerals are not composed of an organic material.
- *Solid:* The minerals are in solid form at normal temperature and pressure, although there are exceptions, such as mercury.
- *Definite chemical composition:* The minerals have a definite chemical composition, although they can be composed of two or more elements.
- *Ordered internal structure:* The minerals are crystalline, meaning that their atoms are arranged in an ordered pattern.

The International Mineralogical Association (IMA) is the governing body that accepts the discovery of new minerals. As of 2025, there are over 5,700 officially recognized species of minerals, and dozens of new ones are being discovered each year (Figure 1) [3].

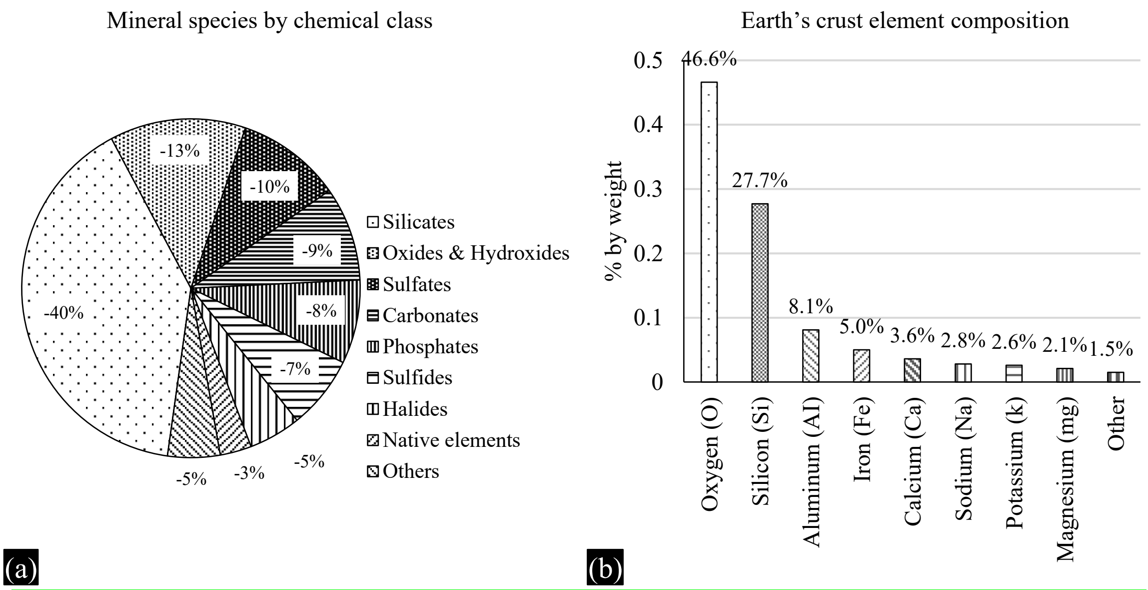

Figure 1. Distribution of mineral species by chemical class (left) and composition of Earth's crust by element weight percentage (right).

Classification Systems

There are a number of classification systems used to classify minerals. Some of these classification systems are as follows:

Dana Classification System

The Dana classification system was first formulated by an American mineralogist named James Dwight Dana in 1837. This system has undergone a number of changes since its formulation [3]. The Dana classification system primarily classifies minerals into classes on the basis of anion or anionic group. The classes in this system are as follows:

1. Native elements (gold, diamond, sulfur)

2. Sulfides and sulfosalts (pyrite, galena, chalcopyrite)
3. Oxides and hydroxides (hematite, magnetite, corundum)
4. Halides (halite, fluorite, sylvite)
5. Carbonates, nitrates, borates (calcite, dolomite, malachite)
6. Phosphates, arsenates, vanadates (apatite, (e.g., apatite, turquoise, vanadinite)
7. Sulfates, Chromates, Molybdates, and Tungstates (e.g., gypsum, barite, wolframite)
8. Silicates (e.g., quartz, feldspar, mica, pyroxene, amphibole)

Strunz Classification System

The Strunz Mineralogical Tables, developed by Karl Hugo Strunz and widely used in Europe, similarly classify minerals by chemical composition and crystal structure. The 10th edition (2001) organizes minerals into 10 classes: elements, sulfides, halides, oxides, carbonates, borates, sulfates, phosphates, silicates, and organic minerals [4].

Rock-Forming vs. Ore Minerals

A practical distinction exists between rock-forming minerals (quartz, feldspar, mica, pyroxene, amphibole, olivine, calcite) and ore minerals (chalcopyrite for copper, sphalerite for zinc, magnetite for iron). Industrial minerals are a third category: non-metallic minerals valued for their physical or chemical properties, such as talc, kaolin, and asbestos [5].

PHYSICAL AND CHEMICAL PROPERTIES

The identification of a mineral in its field setting as well as in a laboratory setting is made possible by a number of distinct physical and chemical properties. The physical and chemical properties of a mineral are direct manifestations of its internal atomic structure and chemical composition [6].

Crystal System and Habit

All minerals are known to crystallize in one of seven distinct crystal systems: Isometric (or cubic), Tetragonal, Orthorhombic, Hexagonal, Trigonal, Monoclinic, and Triclinic. The habit of a mineral refers to its external shape. The external shape of a mineral crystal can vary from cubic (halite), octahedral (magnetite), to prismatic (tourmaline), acicular (needle-shaped), platy, or massive (Figure 2).

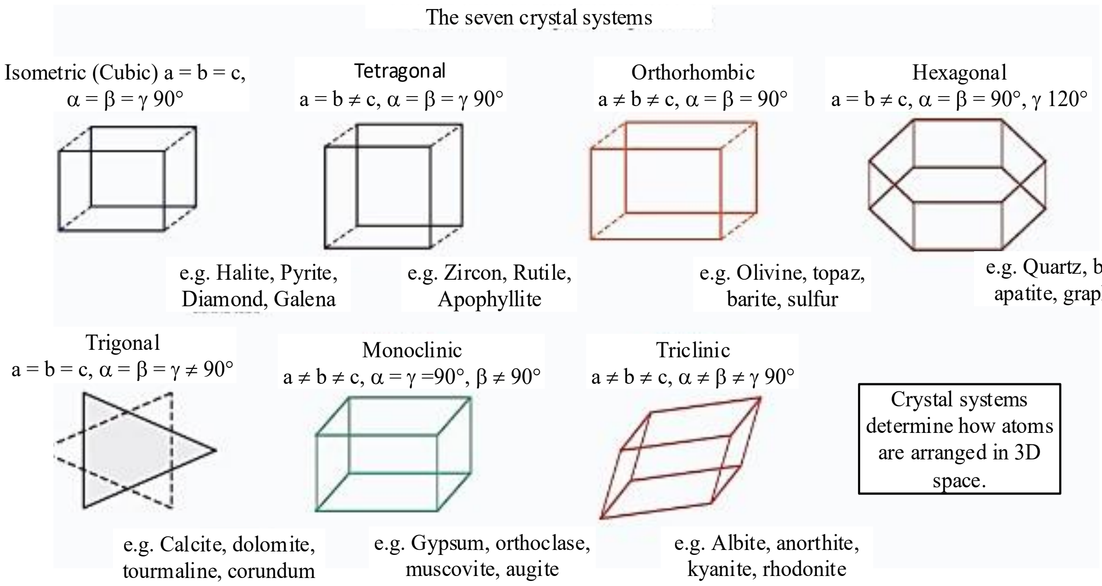

Figure 2. The seven crystal systems with representative examples. Each system is defined by distinct axial lengths and inter-axial angles.

Hardness

Hardness measures a mineral's resistance to scratching and is quantified using the Mohs hardness scale, devised by Friedrich Mohs in 1812. The scale ranges from 1 (softest) to 10 (hardest) (Table 1 & Figure 3):

Cleavage, Fracture, and Parting

Cleavage is the property of a mineral that allows it to break or cleave in certain directions where the bonds between the atoms are relatively weak. The cleavage of a mineral is described in terms of the cleavage direction and the cleavage quality. Mica has perfect cleavage in the basal direction, whereas the cleavage of the mineral halite is perfect in the cubic direction in three directions. Fracture is the property of a mineral that allows it to break irregularly in a manner that is not related to cleavage. The fracture of a mineral may be conchoidal (curved or shell-like, as in the case of quartz and obsidian), fibrous [7].

Table 1. The Mohs hardness scale.

Mohs Value	Mineral	Common Test
1	Talc	Easily scratched by fingernail
2	Gypsum	Scratched by fingernail (2.5)
3	Calcite	Scratched by a copper coin (3.5)
4	Fluorite	Scratched by a steel knife (5.5)
5	Apatite	Scratched by steel, scratches glass
6	Orthoclase Feldspar	Scratches glass easily
7	Quartz	Scratches steel and glass
8	Topaz	Scratches quartz
9	Corundum	Scratches topaz; only diamond harder
10	Diamond	Hardest known natural substance

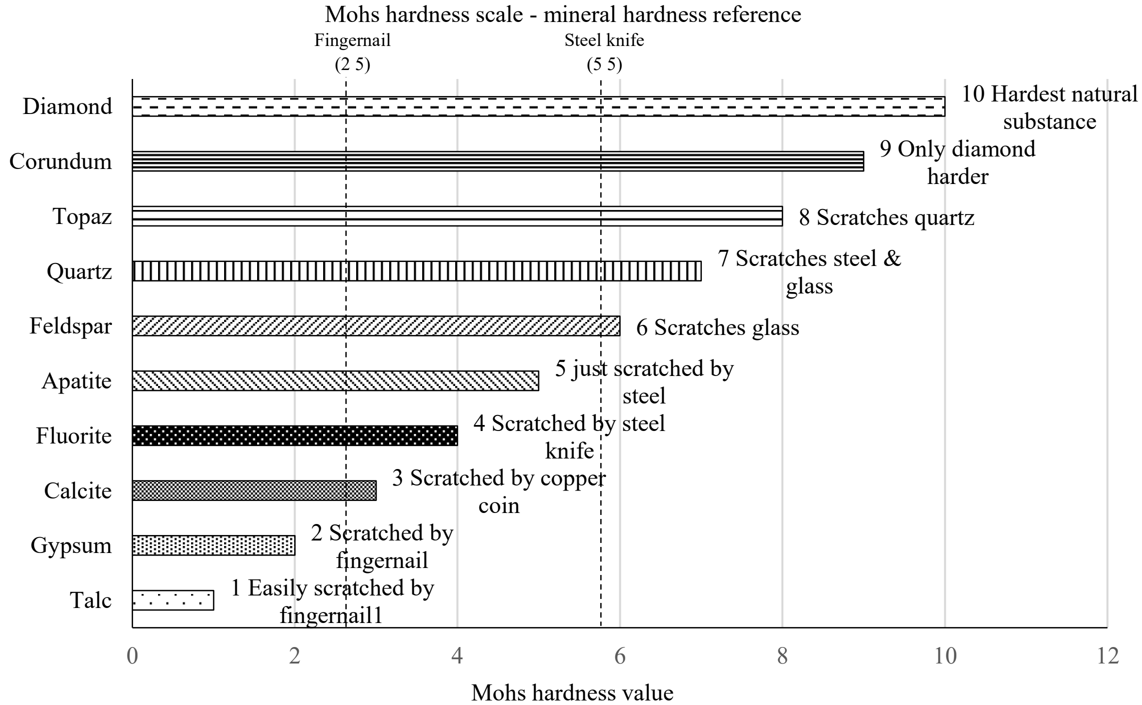

Figure 3. Visual representation of the Mohs hardness scale with reference test materials and common household objects.

Luster, Color, and Streak

The luster of a mineral refers to the way its surface reflects light. Minerals with metallic luster include pyrite, galena, and native gold. Nonmetallic lusters include vitreous (glassy, or quartz), resinous (sphalerite), adamantine (diamond), pearly, silky, and earthy. Color varies greatly among minerals. Many minerals come in a variety of colors depending on the amount of impurities present. Streak refers to the color of a mineral's powder when scratched on an unglazed porcelain streak plate. Streak is a more reliable method for identifying a mineral than its color. Hematite, for instance, may be black or silver, but its streak is always a characteristic red-brown [8].

Specific Gravity and Other Properties

Specific gravity is the ratio of the density of a mineral to the density of water. Specific gravity is one of the most important properties used to identify minerals. Specific gravity of most silicate rock-forming minerals ranges from 2.6 to 3.5. Metallic ore minerals have high specific gravity: gold (~19.3), galena (~7.6), and magnetite (~5.2). Other important properties that may be used to identify minerals include magnetism, fluorescence under ultraviolet light, radioactivity, taste (halite), solubility in hydrochloric acid (calcite effervesces vigorously), and tenacity [9].

MINERAL FORMATION AND GEOLOGICAL OCCURRENCE

Minerals are formed by various geological processes, each of which has distinguishing characteristics.

Magmatic and Ignite Processes

During the cooling process of magma, minerals precipitate in a particular order, as described by Bowen's reaction series. High-temperature minerals such as olivine and pyroxene precipitate first, followed by low-temperature minerals such as quartz and potassium feldspar. The assemblage of minerals in an igneous rock is related to the composition of the original magma. Pegmatites, which are coarse-grained igneous rocks, are economically important for rare minerals such as tourmaline, topaz, beryl, and rare earth element (REE) phosphates, as well as lithium minerals such as spodumene and lepidolite [10].

Hydrothermal Processes

The process of hydrothermal deposits refers to the movement of hot, mineral-laden fluids in fractures and pore spaces in the Earth's crust. As the fluids lose heat, minerals are precipitated. Hydrothermal deposits are among the most important mineral deposits. These deposits contain important amounts of gold, silver, copper, lead, zinc, tin, tungsten, and molybdenum. Quartz veins that contain gold and sulfides are hydrothermal deposits. Submarine hydrothermal deposits, also known as black smokers, are found along the mid-ocean ridges. These deposits contain massive sulfides, copper, zinc, and iron.

Sedimentary Processes

The process of sedimentation by chemical precipitation from evaporating seawater or lake water results in the formation of evaporite deposits. These deposits contain halite, gypsum, and anhydrite. Biochemical precipitation by organisms results in the formation of carbonate deposits, such as limestone, chalk, and silica, such as chert and diatomite. In the process of clastic sedimentation, heavy minerals such as gold, platinum, diamonds, ilmenite, rutile, zircon, and cassiterite are concentrated in placer deposits.

Metamorphic Processes

Heat, pressure, and chemically active fluids are involved in the metamorphism of pre-existing minerals, leading to the formation of new minerals that are characteristic of certain metamorphic conditions of pressure and temperature. The metamorphic minerals chlorite, biotite, garnet, staurolite, kyanite, and sillimanite are called index minerals and are used to determine the metamorphic grade. Contact metamorphism in the vicinity of igneous intrusions gives rise to skarn deposits, where economically important minerals like magnetite, scheelite, and wollastonite are found.

Weathering and Supergene Processes

Weathering of primary minerals on the Earth's surface involves the breakdown of primary minerals and the formation of secondary minerals. Feldspars are converted to clay minerals like kaolinite and montmorillonite, and olivine and pyroxene are converted to serpentine, talc, and chlorite, and pyrite is converted to goethite and limonite. Supergene enrichment in the zone of oxidation overlying an ore

MAJOR MINERAL GROUPS

Silicates

The silicates constitute the largest group of the mineral kingdom, and they account for 90% of the Earth's crust by volume. Their building blocks are the $[SiO_4]$4- tetrahedra. Silicates are classified according to the polymerization of the tetrahedra:

- Nesosilicates (Island Silicates): Comprise isolated tetrahedra; e.g., olivine [(Mg, Fe)2SiO_4], garnet, zircon, topaz, and staurolite.
- Sorosilicates (Pair Silicates): Comprise two tetrahedra sharing a common oxygen; e.g., epidote and hemimorphite.
- Cyclosilicates (Ring Silicates): Comprise a number of tetrahedra linked to form a ring; e.g., beryl [Be3$Al_2Si_6O_{18}$] and tourmaline.
- Inosilicates (chain silicates): Single chains (pyroxenes) or double chains (amphiboles).
- Phyllosilicates (sheet silicates): Infinite sheets; e.g., micas, clay minerals, talc, serpentine, chlorite.
- Tectosilicates (framework silicates): Three-dimensional frameworks; e.g., quartz (SiO_2), feldspars, zeolites.

Carbonates

Carbonates contain the anion $[CO_3]$2-. The main rock-forming carbonates are calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)$2]. The other important carbonates are aragonite (another form of $CaCO_3$), siderite ($FeCO_3$), rhodochrosite ($MnCO_3$), magnesite ($MgCO_3$), malachite [Cu2$(CO_3)(OH)_2$], and azurite [$Cu_3(CO_3)_2(OH)_2$].

Oxides and Hydroxides

The oxide group consists of hematite (Fe_2O_3), corundum (Al_2O_3, with varieties ruby and sapphire), cassiterite (SnO_2, tin ore), rutile (TiO_2), and spinel group minerals. The oxide class provides some of the world's most important iron, manganese, chromium, tin, and titanium ore minerals.

Sulfides and Native Elements

Sulfide minerals are the principal ores of many metals: pyrite (FeS2), chalcopyrite (CuFeS2), galena (PbS), sphalerite (ZnS), cinnabar (HgS), molybdenite (MoS2), and pentlandite [(Fe,Ni)9S8]. Native elements include gold, silver, copper, platinum-group elements, diamond and graphite (both carbon polymorphs), sulfur, and bismuth. Placer gold deposits result from the fluvial concentration of native gold.

Phosphates, Halides, and Other Groups

Phosphates are a group of mineral salts that are usually associated with the anion $[PO_4]$3- and include: Apatite, which contains fluorine, chlorine, or hydroxyl ions along with phosphate. Apatite is the most common phosphate mineral. The mineral minerals include halite (NaCl), fluorite (CaF_2), and sylvite (KCl). Sulfates include gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite ($CaSO_4$), and barite ($BaSO_4$). Borates (e.g., borax, ulexite) are important industrial minerals.

ECONOMIC AND INDUSTRIAL APPLICATIONS

Metals and Metallurgy

The extraction of metals from their ore minerals forms the basis of metallurgy. The iron ore minerals, such as hematite, magnetite, and goethite, are the source for the steel industry, which manufactures over 1.9 billion tonnes of steel annually. Copper ore minerals, such as chalcopyrite, bornite, and malachite, are smelted to produce copper for wiring and plumbing. Aluminum is produced by the extraction of bauxite, while the precious metals, such as gold, silver, and platinum, are obtained by the extraction of native elements and their sulfide minerals.

Construction and Industrial Minerals

Table 1.

Mineral	Key Property	Application
Gypsum	Soft, hydrated sulfate	Plasterboard, cement retarder, soil amendment
Calcite / Limestone	Calcium carbonate	Cement, lime production, paper filler
Talc	Soft, hydrophobic	Ceramics, paints, pharmaceuticals, cosmetics
Kaolin	White clay	Paper coating, ceramics, rubber filler
Fluorite	Flux, fluorine source	Steel industry, hydrofluoric acid production
Apatite	Phosphate mineral	Phosphate fertilizers, animal feed
Quartz (silica sand)	High $SiO2$ purity	Glass, foundry sand, hydraulic fracturing
Halite	Soluble salt	Food seasoning, chemical industry, de-icing
Graphite	Conductor, lubricant	Batteries, lubricants, pencils, electrodes
Mica	Electrical insulator, heat resistant	Electronics, cosmetics, drilling fluids

Gemstones

Gemstones are minerals that are prized for their beauty, hardness, and rarity. The hardest and most valuable gemstone is diamond, an allotrope of carbon. The variety of corundum includes ruby, colored red by chromium, and sapphire, colored blue by iron and titanium. Beryl includes emerald, colored green by chromium, and aquamarine, colored blue-green by iron. Other gemstones are tourmaline, topaz, spinel, tanzanite, a variety of zoisite, alexandrite, a variety of chrysoberyl, and opal, an amorphous form of silica [11].

Critical Minerals for Modern Technology

The 21st century has recognized a new class of economically essential minerals that are strategically significant and whose supply could be subject to interruption. These are lithium, used in batteries, cobalt, used in the cathode of batteries, rare earth elements, used in magnets and phosphors, nickel, used in batteries and stainless steel, manganese, used in steel and batteries, graphite, used in the anode of batteries, platinum group elements, used in catalytic converters and fuel cells, and semiconductor minerals, used in semiconductors, comprising indium, gallium (Figure 4).

ENVIRONMENTAL AND SUSTAINABILITY CONSIDERATIONS

Mining and Environmental Impact

Mining has inherent environmental impacts. In open-pit mines, waste rock can be massive, and underground mines can have significant volumes of waste rock. Acid mine drainage (AMD) occurs when sulfide minerals, especially iron pyrite, react with air and water. The result is an extremely acidic water with dissolved metals, which can decimate aquatic life. Large-scale land clearing for mining can cause habitat destruction; smelting operations can release sulfur dioxide; and artisanal small-scale mining (ASGM) for gold, which often uses mercury, can result in significant mercury pollution.

Sustainable Mining Practices

Significant technologies and practices have been developed to reduce the impact of mining:

- Paste tailings technology to conserve water and prevent failures of tailings dams.
- Treatment of AMD using lime neutralization, constructed wetlands, or passive bioremediation.
- Ongoing rehabilitation of mined land.
- Improvements to flotation cells to optimize recovery of minerals and reduce waste.
- Circular Economy – recycling metals from electronic waste (‘urban mining’) to reduce primary extraction.

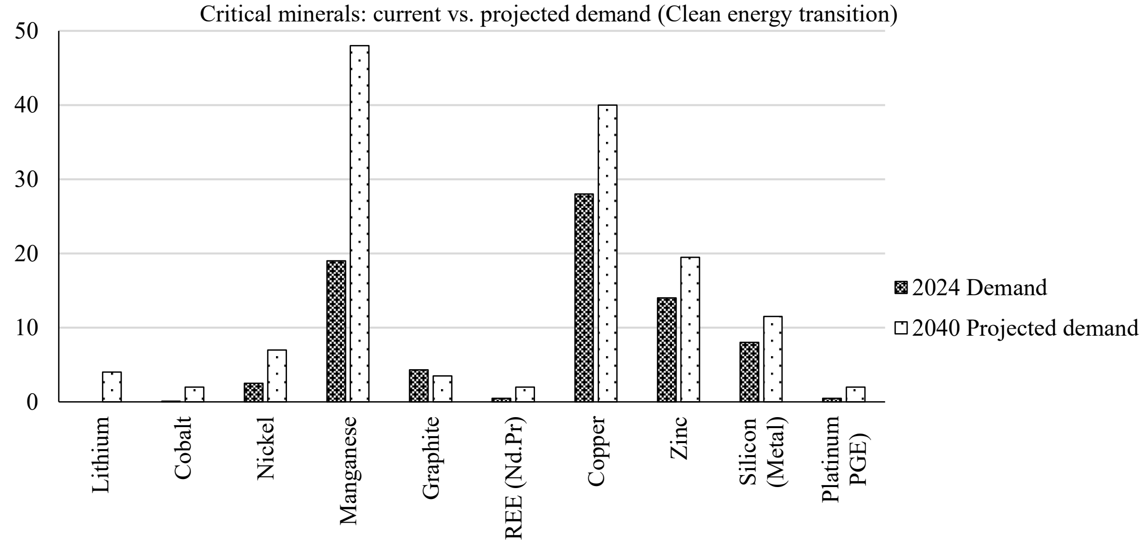

Figure 4. Current (2024) versus projected (2040) demand for key critical minerals driven by the global clean energy transition, showing demand multipliers up to ×19 for lithium.

Minerals and Human Health

Minerals play important roles in maintaining human health. For example, calcium from calcium phosphate minerals in food is important for maintaining healthy bones and teeth. Iron, which occurs in haematite, haematite, and magnetite, plays a vital role in the blood. Other important trace elements include zinc, selenium, magnesium, manganese, and iodine. There are also minerals that are hazardous to health. For example, amphiboles and serpentine asbestos are responsible for mesothelioma and respiratory diseases. Silica dust from mining operations can cause silicosis. Heavy metal minerals like galena, cinnabar, and arsenopyrite can cause lead, mercury, and arsenic poisoning.

Geochemical Cycling and Climate

Mineral reactions are important in the long-term carbon cycle and the global nutrient cycle, which control global climate. Weathering of silicate minerals reacts with carbon dioxide in the atmosphere to produce calcium carbonate, which dissolves calcium and bicarbonate into the oceans, where they become part of carbonate minerals—a key process that controls Phanerozoic climates. Hydrogen gas is produced as ultramafic minerals undergo serpentinization.

FRONTIERS IN MINERALOGY RESEARCH

Nano mineralogy

The development of new techniques in electron microscopy, such as TEM and STEM-EDS, as well as synchrotron X-ray diffraction and atom probe tomography, has led to the emergence of nano mineralogy. The importance of nanoparticulate minerals in soil chemistry, environmental remediation, and the genesis of ore deposits is now recognized. New phases of minerals and textures that could not be resolved using microscale techniques are now accessible, revolutionizing our understanding of mineral reactions, diffusion, and defects.

Planetary Mineralogy

The exploration of other planets in the solar system using space exploration techniques has greatly expanded our understanding of the variety of minerals beyond the Earth. The rovers sent to Mars, such as the Curiosity and Perseverance rovers, have identified the minerals phyllosilicate, sulfate, carbonate, and perchlorate on Mars. The Hayabusa2 mission, which sampled the asteroid Ryugu, and the OSIRIS-REx mission, which sampled the asteroid Bennu, have identified the minerals hydrated silicate and organic compound. The Dawn mission identified the minerals carbonate and halide on the dwarf planet Ceres. These discoveries expand the definition of mineralogy to encompass all solid bodies in the solar system.

Machine Learning in Mineralogy

Artificial intelligence and machine learning techniques are being used for mineral identification, automated mineralogy (QEMSCAN, MLA), spectral analysis (hyperspectral remote sensing and drill core analysis), and predictive modeling of mineral stability and formation. These techniques, using neural networks and spectral libraries, enable the identification of minerals using remote sensing data, from the field to satellite-based, to speed up the search for critical mineral deposits.

New Mineral Discoveries

On average, 100 new mineral species are approved by the IMA annually. New discoveries have included minerals discovered in meteorites, moon rocks, and unusual geological settings, such as coal fires. Novel synthetic analogs of natural minerals stable at very high pressure, e.g., post-perovskite MgSiO3, bridgmanite, shed light on the mineralogy of the Earth's lower mantle and exoplanet cores.

CONCLUSION

Minerals are the indispensible building blocks of Earth's crust, the feedstock of human civilization, and the subject of one of humanity's oldest and most dynamic scientific disciplines. From the humble clay minerals that underpin agriculture and ceramics to the rare earth and lithium minerals driving humanity's energy revolution, mineralogy is relevant to all aspects of human endeavor and scientific understanding.

This paper has briefly discussed all of the main aspects of mineralogy: the five-part scientific definition and classification systems; the physical and chemical identification criteria; the varied geological mechanisms of mineral formation; the main chemical groups and their characteristic species; the varied economic applications from metallurgy to gemstones to strategic minerals; and environmental and health aspects of mineral extraction and geochemical cycles.

With regard to the future, it is clear that a convergence of nanoscale characterization techniques, planetary exploration, artificial intelligence, and circular economy approaches is revolutionizing both the art and science of mineralogy. A sustainable and equitable supply of critical minerals in a way that does not damage the environment is one of the great technological and geopolitical challenges of the next several decades. A deep understanding of mineralogy – its properties, origins, distribution, and activities – is a critical part of this solution.

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