Roles of the Chemical Elements in Facilitating Life on Earth

By Philip E Gibbs

Abstract: Many of the elements in the periodic table play a part in supporting life, either directly in biochemistry or indirectly in some supporting role. This is a catalogue of how each element is used, updated to reflect recent discoveries in marine biology, microbial metabolism, and structural biochemistry. This paper is a substantial revision and update of an earlier review [1].

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1. HYDROGEN

Forms water with oxygen.

Hydrogen is one of the basic elements of organic chemistry and may be considered the second most important element for life. Present in all organic molecules where it forms a single bond with carbon enabling chain molecules to form. It is present in proteins, sugars, nucleic acids [1].

Hydrogen formed in the early universe and is the most abundant element today. It continues to be the main source of energy by fusion to helium in the Sun's core.

2. HELIUM

Chemically inert, but an important step in the abundant synthesis of elements because three helium nuclei can fuse to form carbon (triple-alpha process).

Helium nuclei also form alpha radiation e.g. from radon gas, so can be linked to genetic mutations. It is also responsible for decay of Uranium-238 and Thorium-232 which heat the Earth's core.

Helium is also the by-product of nuclear fusion in the Sun's core.

3. LITHIUM

Lithium is a rare element on Earth, which is convenient because in large quantities it is harmful.

Lithium is used pharmacologically as a mood stabiliser, particularly for bipolar disorder, but should not be used whilst pregnant due to risk of birth defects. Whilst some research suggests trace lithium may have neuroprotective or other benefits [2], **lithium is not established as an essential nutrient for humans**. The therapeutic effects are pharmacological rather than nutritional, and treatment can have side effects including hypothyroidism and kidney problems.

4. BERYLLIUM

Beryllium is a rare light element with **no known biological function**.

Beryllium-8 has a very short half-life but its energy levels are tuned along with those of carbon-12 to allow synthesis through nuclear fusion of helium to form carbon-12 (Hoyle resonance).

Beryllium is toxic to humans, not essential. Exposure causes berylliosis, a serious lung disease characterised by weight loss, fatigue, and respiratory problems. There is no such thing as beryllium deficiency in biological systems [3].

5. BORON

Boron is essential for plants in small amounts to strengthen cell walls through crosslinking of pectin and other polysaccharides.

In animals it is essential in trace amounts for the metabolism of calcium, magnesium, and phosphorus used to form bones and teeth.

Boron deficiency causes osteoporosis and impaired bone development [4].

6. CARBON

Carbon is the defining element of organic chemistry and the most important element for life. Its four covalent bonds allow it to form complex chain and branching molecules. It can form stable bonds with a variety of other elements including hydrogen, oxygen, nitrogen, phosphorus and sulphur which are important in nucleic acids and proteins. It can also form strong double and triple bonds [1].

Carbon reacts with oxygen to form carbon dioxide, an important molecule in the carbon cycle between plants and animals.

7. NITROGEN

Nitrogen is the fourth most important element for life after carbon, hydrogen and oxygen. It is a component of amino acids which are the building blocks of proteins. It is also present in urea, nucleic acids, and many other biomolecules including neurotransmitters and ATP [1].

The nitrogen cycle involves fixation from atmospheric N_2 into ammonia by specialised bacteria containing nitrogenase enzymes, then incorporation into biomolecules, and eventual return to the atmosphere through denitrification.

8. OXYGEN

Oxygen is the third most important element for life. It is taken in from the atmosphere by animals to metabolise carbohydrates for energy through aerobic respiration. Plants produce oxygen from carbon dioxide by photosynthesis [1,5].

Oxygen forms water with hydrogen.

Oxygen is present in most organic compounds including all proteins, carbohydrates, and nucleic acids.

As ozone (O_3) in the upper atmosphere it also protects life from harmful ultraviolet radiation.

9. FLUORINE

Fluorine is used by some microorganisms and plants but is **not essential for animals**. However, fluoride (F^-) is **beneficial for dental health** by strengthening tooth enamel and reducing cavities through conversion of hydroxyapatite to fluorapatite. It should be considered beneficial rather than essential, with toxicity occurring at excessive doses (fluorosis) [7].

Fluorine also has been shown to have pharmacological effects, such as reducing the effects of iron deficiency in experimental animals [2].

10. NEON

The noble gas neon is the fifth most abundant element in the universe, but because it is inert and rare on Earth it plays no role in biology.

11. SODIUM

Sodium in salt (NaCl) is required in significant quantities in animals to ensure the right electrolyte balance. Too much or too little causes life-threatening problems so it is regulated in the blood by the kidneys.

Sodium is critical for the generation of nerve impulses and muscle contraction. The **Na^+/K^+-ATPase pump** maintains the electrochemical gradient across cell membranes, which is fundamental to cellular energetics, signalling, and homeostasis across all domains of life [8].

The presence of sodium in animals may also be linked to its concentration in sea water where sea-life must keep an electrolyte balance with its environment.

12. MAGNESIUM

Magnesium is an essential element in biological systems, being present in every cell. ATP, the universal source of energy in cells, can only function when bound to a magnesium ion (Mg-ATP complex) [1].

It stabilises all organic compounds that contain phosphate including RNA and DNA by coordinating phosphate groups.

Magnesium has catalytic properties facilitating biochemical reactions in over 300 known enzymes.

Another important example in plants is that magnesium forms the central atom of chlorophyll, essential for photosynthesis.

Magnesium deficiency in animals can cause a wide range of severe symptoms including muscle spasms, cardiac arrhythmias, and neurological problems.

13. ALUMINIUM

Aluminium is one of the few reactive elements that does not play a significant role in biology. Although its abundance in the universe is low (0.005%), it is the third most common element in the Earth's crust after oxygen and silicon. **With this sole exception, the eight most abundant elements in Earth's crust are also essential for life** [2]. Aluminium's primary role is therefore to help form the rocky substrate on which life can thrive.

Aluminium can be toxic to plants in acidic soils and to aquatic life at elevated concentrations.

14. SILICON

Silicon has been proposed as an alternative to carbon as a basis for life, but it is much less versatile in its chemical bonds with other elements.

However, silicon is essential for certain life forms. Most notably, **diatoms require silicon to build their silica frustules** (cell walls), and these microscopic algae are responsible for approximately 20% of global primary production and oxygen generation [9,10,11]. Many sponges also biosilicify, incorporating silicon into their structural elements (spicules). Silicon is absorbed by most plants and may aid in structural support and stress resistance.

In humans, silicon may play roles in bone formation and connective tissue health, though essentiality remains debated.

The main geological role of silicon is forming the Earth's crust (silicon dioxide and silicates) on which terrestrial life exists.

15. PHOSPHORUS

Phosphorus is the fifth most important element in biochemistry. It is crucial in RNA, DNA and especially ATP (adenosine triphosphate), the energy currency of cells. Phosphate groups also play central roles in cell signalling through protein phosphorylation [1].

Phosphorus forms the backbone of nucleic acids through phosphodiester bonds and is a major component of cell membranes (phospholipids).

It has been speculated that arsenic could potentially replace the role of phosphorus in primitive life, but this has never been demonstrated. Follow-up studies refuted claims of arsenic incorporation into DNA in bacteria [12].

16. SULPHUR

Sulphur is the sixth and last in the list of essential elements for the basics of life as we know it (C, H, N, O, P, S).

Sulphur is a component of the amino acids cysteine and methionine. Disulphide bonds between cysteine residues are critical for protein structure and stability [1].

Sulphur is also present in coenzyme A, biotin, and various other biomolecules.

Sulphur deficiency causes physical deformities, mental retardation, and can be fatal.

17. CHLORINE

Chlorine combined with sodium forms common salt (NaCl) which is important for electrolyte balance in the body, working in concert with potassium through the **Na^+/K^+-ATPase** to maintain membrane potentials [7].

As a constituent in hydrochloric acid (HCl), chloride ions are important for digestion in the stomach.

Chloride channels are also important for maintaining cellular pH and volume regulation.

Chloride ions are essential cofactors in photosynthesis, playing a critical role in the oxygen-evolving complex of Photosystem II where they facilitate water oxidation [13].

18. ARGON

As a rare noble gas, argon is chemically inert and not used in biology.

19. POTASSIUM

Potassium is the main intracellular ion for all types of cells. It complements sodium in providing electrolyte balance through the **Na^+/K^+-ATPase pump**, which actively transports Na^+ out and K^+ into cells, creating the electrochemical gradients essential for nerve impulses, muscle contraction, and cellular energetics [7].

Potassium is critical in neurotransmission, muscle contraction and heart function. Deficiency increases risk of hypertension, stroke and cardiovascular disease.

Radioactive decay of Potassium-40 was a main contributor to heating the Earth's core in its early history and continues to provide geothermal energy today.

20. CALCIUM

Calcium is well known in biology for forming bones and teeth (as hydroxyapatite), however it has many other important roles.

Calcium ions (Ca^{2+}) are critical second messengers in signal transduction pathways controlling muscle contraction, neurotransmitter release, fertilisation, and numerous other cellular processes [1].

It is a cofactor of many enzymes, especially those involved in blood-clotting cascades.

Calcium also plays structural roles in cell walls of plants and stabilises membrane structures.

21. SCANDIUM

Although scandium is not especially rare in the Earth's crust, it has very little impact on biology. It is not used in any known biochemical process and is not particularly toxic in normal quantities.

22. TITANIUM

Titanium has no confirmed biological role. Most living species appear to have no use for titanium. Whilst some organisms can sequester titanium (possibly sea squirts), this likely represents environmental contamination rather than biological function.

Early speculation that titanium dioxide might substitute for chlorophyll in some bacteria lacks supporting evidence and should be considered unsubstantiated.

23. VANADIUM

Vanadium is used in some marine species in particular.

Some bacteria use vanadium-containing nitrogenase for nitrogen fixation (an alternative to the more common molybdenum-dependent enzyme).

Vanadium is also essential in ascidians (sea squirts) and tunicates where it accumulates to high concentrations in blood cells, though its exact purpose remains unclear.

In mammals, vanadium may have insulin-mimetic properties and could promote growth, though essentiality is not established.

24. CHROMIUM

Chromium was traditionally believed to be essential for insulin function and glucose metabolism (as the "glucose tolerance factor"). However, **the essentiality of chromium in humans is now debated and controversial**, with more recent research questioning whether chromium deficiency causes disease in humans under normal conditions [14,15].

25. MANGANESE

Manganese is an important element for human health, essential for development, metabolism, and the antioxidant system (as a cofactor in manganese superoxide dismutase, Mn-SOD) [1].

The most significant role of manganese is in the oxygen-evolving complex (OEC) of Photosystem II. The Mn_4CaO_5 cluster catalyses water splitting to produce molecular oxygen, making it responsible for generating most of Earth's atmospheric oxygen through photosynthesis. This is arguably the most important biogeochemical function of any trace element [13,16].

26. IRON

The most important role for iron is as the active component in haemoglobin and myoglobin for carrying and storing oxygen in animals [1].

Iron is also used in cytochromes for electron transport chains, in **iron-sulphur clusters** in numerous enzymes [17], and in redox enzymes such as catalase and peroxidase.

A non-biological role of iron that is important for life is forming the Earth's molten core where it is responsible for generating the magnetic field that protects the planet and its atmosphere from the solar wind. This magnetic shield prevents atmospheric stripping and protects life from harmful cosmic radiation.

27. COBALT

Cobalt is essential for the metabolism of all animals. It is the central metal atom in **vitamin B12 (cobalamin)**, which is required for DNA synthesis, red blood cell formation, and neurological function [18].

Some bacteria and archaea also use cobalt in other enzymes beyond B12.

28. NICKEL

Nickel plays important roles in the biology of some plants, eubacteria, archaebacteria, and fungi.

Nickel is the active site metal in urease (which catalyses urea hydrolysis) **and in various hydrogenases** (which catalyse hydrogen oxidation and production). These are found across diverse microbial species and some plants [19,20].

Nickel released from Siberian Traps volcanic eruptions is suspected of facilitating the growth of Methanosarcina, a genus of methanogenic archaea that produced methane during the Permian-Triassic extinction event 250 million years ago, potentially contributing to the extinction.

29. COPPER

Copper is a component of proteins involved in oxygen transportation (haemocyanin in invertebrates) and electron transfer. Copper-based oxygen transport evolved when cyanobacteria produced oxygen in the atmosphere [5], before iron became the dominant oxygen carrier in vertebrates.

Copper remains essential at the cellular and sub-cellular level in cytochrome c oxidase (the terminal enzyme in the electron transport chain), in superoxide dismutase (Cu/Zn-SOD), and in other enzymes involved in iron metabolism, neurotransmitter synthesis, and connective tissue formation [21].

30. ZINC

Zinc is the only metal that appears in all six enzyme classes and is the second most abundant transition metal in organisms after iron [3,22].

Zinc fingers are critical DNA-binding structural motifs in transcription factors. In the brain, zinc is stored in specific synaptic vesicles by glutamatergic neurones and modulates neuronal excitability.

Zinc plays numerous other roles including immune function, protein synthesis, wound healing, and as a cofactor in over 300 enzymes including carbonic anhydrase, alcohol dehydrogenase, and alkaline phosphatase [22].

31. GALLIUM

Gallium has no known natural role in biology.

32. GERMANIUM

Germanium is not considered essential to the health of plants or animals.

33. ARSENIC

Some species of bacteria can obtain their energy by oxidising various fuels whilst reducing arsenate (AsO_4^{3-}) to arsenite (AsO_3^{3-}), using arsenic in anaerobic respiration.

Whilst once speculated to substitute for phosphorus in DNA, this has been definitively refuted [11].

34. SELENIUM

Selenium is a component of the unusual amino acids **selenocysteine and selenomethionine**. Selenocysteine is sometimes called the "21st amino acid" and is incorporated into selenoproteins, which include glutathione peroxidases and thioredoxin reductases essential for antioxidant defence [23].

Selenium deficiency causes serious health problems including Keshan disease (cardiomyopathy) and reduced immune function.

35. BROMINE

Bromine is abundant in the sea and brominated compounds play important roles in the function of many marine algae.

Bromine is now recognised as essential for animals, not merely beneficial. Since 2014, research has shown that the enzyme **peroxidasin uses hypobromous acid (HOBr) to form sulphilimine crosslinks in collagen IV**, which are critical for basement membrane structure and tissue integrity. Dietary bromine deficiency is lethal in Drosophila and can be rescued by bromide supplementation, confirming essentiality across Metazoa [24].

Additionally, **eosinophils preferentially use bromide to generate halogenating agents** for immune defence, demonstrating another important biological role for bromine in animals [25].

36. KRYPTON

Krypton is a noble gas and chemically inert, playing no role in biology.

37. RUBIDIUM

Rubidium has no known essential biological role. However, because it is chemically similar to potassium, organisms inadvertently absorb rubidium from food. The average human body contains approximately 360 mg of rubidium, which is taken up by the same transport mechanisms as potassium.

38. STRONTIUM

Acantharea, a relatively large group of marine radiolarian protozoa, produce intricate mineral skeletons composed of strontium sulphate (celestite). This represents one of the few biological uses of strontium.

Strontium can also substitute for calcium in bones, though this is not a normal biological function.

39. YTTRIUM

Yttrium has no known biological role.

40. ZIRCONIUM

Zirconium has no known biological role.

41. NIOBIUM

Niobium has no known biological role.

42. MOLYBDENUM

Molybdenum is an active element in enzymes that fix nitrogen, forming ammonia from atmospheric N_2. This is accomplished by the **molybdenum-iron cofactor (FeMo-co) in nitrogenase**, found in certain bacteria and then reused by plants and animals throughout the food chain.

Molybdenum is also present in the **molybdenum cofactor (Moco)**, which is used in enzymes involved in purine catabolism, sulphite detoxification, and other processes. The unique redox chemistry of molybdenum makes it particularly suited to catalysing oxygen-atom transfer reactions [32,33].

A scarcity of molybdenum in the early oceans may have been a limiting factor for biological nitrogen fixation and evolution for the first 2 billion years of Earth's history [34].

43. TECHNETIUM

Technetium has no stable isotopes and no biological role (all isotopes are radioactive).

44. RUTHENIUM

Ruthenium has no known biological role.

45. RHODIUM

Rhodium has no known biological role.

46. PALLADIUM

Palladium has no known biological role.

47. SILVER

Silver has antimicrobial properties but no known essential biological function. It is toxic to microorganisms, which is why it has been used historically for water purification and wound treatment.

48. CADMIUM

Cadmium is generally toxic to most organisms, causing kidney damage and other serious health effects.

However, cadmium has a bona fide biological role in certain marine organisms. A marine diatom (*Thalassiosira weissflogii*) uses a **cadmium-dependent carbonic anhydrase (CDCA1)** when zinc is scarce. This enzyme is naturally cambialistic (can use either Cd^{2+} or Zn^{2+}) and represents the first and only known cadmium metalloenzyme. This surprising adaptation allows some phytoplankton to thrive in low-zinc ocean regions [26,27].

49. INDIUM

Indium has no known biological role.

50. TIN

Tin has no confirmed essential biological role in higher organisms, though some studies suggest possible roles in growth and development at trace levels. This remains uncertain.

51. ANTIMONY

Antimony has no known biological role and is generally toxic.

52. TELLURIUM

Tellurium has no known biological role and is toxic to most organisms.

53. IODINE

Iodine is the heaviest element that is essential for most animal life. It is a constituent of thyroid hormones (thyroxine and triiodothyronine), which regulate metabolism, growth, and development [1].

Iodine deficiency is a significant cause of mental retardation (cretinism) and goitre worldwide.

Note: Whilst iodine is the heaviest essential element for animals, tungsten (element 74) is heavier and essential for some microorganisms, so iodine's status as "heaviest essential element" is taxon-dependent.

54. XENON

Xenon is a noble gas generally considered chemically inert. However, **xenon exhibits both anaesthetic and neuroprotective properties** and can activate at least one human transcription factor, despite its usual classification as non-reactive [2]. Nevertheless, xenon has no known essential biological role.

55. CAESIUM

Caesium is chemically similar to potassium and can be absorbed by organisms through potassium transport pathways, but it has no known essential biological function. Radioactive isotopes (e.g., Cs-137) are hazardous.

Some research has suggested potential biological interactions of caesium, though its essentiality remains unproven [28].

56. BARIUM

Barium has limited biological relevance. Some organisms (certain algae) can use barium sulphate in mineral structures, but it is not essential. Barium ions are toxic to most organisms.

57. LANTHANUM

Lanthanum is the first of the lanthanide series, several of which are now recognised as essential for certain microorganisms.

Methylotrophic bacteria (which metabolise single-carbon compounds) **require lanthanides including lanthanum and cerium for XoxF-type methanol dehydrogenases**. These bacteria switch between calcium-dependent and lanthanide-dependent enzymes based on metal availability. Growth rates and gene regulation are lanthanide-dependent in these organisms [29,30,31].

58. CERIUM

Cerium, like lanthanum, is essential for some methylotrophic bacteria that use lanthanide-dependent methanol dehydrogenases. The preference for lighter lanthanides (La, Ce, Pr, Nd) over heavier ones has been demonstrated in enzyme function and cellular uptake [31].

These lanthanide-utilising microbes may play important roles in biogeochemical cycling in environments with available rare earth elements.

59-71. LANTHANIDES (Praseodymium through Lutetium)

Other lanthanides (Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) have similar chemical properties to lanthanum and cerium. **Several of the lighter lanthanides (particularly Nd) are also used by methylotrophic bacteria** [29,30], though La and Ce are the most studied. The heavier lanthanides appear less biologically available and less utilised.

Promethium (61) has no stable isotopes.

72. HAFNIUM

Hafnium has no known biological role.

73. TANTALUM

Tantalum has no known biological role.

74. TUNGSTEN

Tungsten is the heaviest element known to be used in biochemistry, being a component of tungsten-containing enzymes in certain bacteria and archaea.

Tungsten-dependent formate dehydrogenases and aldehyde ferredoxin oxidoreductases are found in hyperthermophilic archaea and some bacteria. These enzymes function in anaerobic metabolism and can catalyse reactions at high temperatures [35,36].

For certain taxa of microorganisms, tungsten is therefore the heaviest essential element, being heavier than iodine (essential for most animals).

75. RHENIUM

Rhenium has no known biological role.

76. OSMIUM

Osmium has no known biological role.

77. IRIDIUM

Iridium has no known biological role.

78. PLATINUM

Platinum has no known natural biological role, though platinum compounds (cisplatin) are used in chemotherapy.

79. GOLD

Gold has no known biological role and is generally biologically inert.

80. MERCURY

Despite its high toxicity to most life, **mercury can serve as an alternative electron acceptor in some purple non-sulphur bacteria** under certain conditions. Mercury ions (Hg^{2+}) can be reduced to volatile Hg^0, which may aid phototrophic metabolism when other electron acceptors are limiting. However, this should not be considered a canonical photosynthetic pathway, but rather an opportunistic detoxification mechanism that can provide metabolic benefits [37].

81. THALLIUM

Thallium is highly toxic and has no known biological role.

82. LEAD

Lead is toxic and has no beneficial biological role.

83. BISMUTH

Bismuth has no known biological role, though bismuth subsalicylate is used medicinally (Pepto-Bismol).

84. POLONIUM

Polonium is highly radioactive and toxic, with no biological role.

85. ASTATINE

Astatine is extremely rare and radioactive, with no biological role.

86. RADON

Radon is a radioactive noble gas that can cause lung cancer through alpha particle emission, but has no biological function.

87. FRANCIUM

Francium is extremely rare and radioactive, with no biological role.

88. RADIUM

Radium is radioactive and toxic, with no biological role.

89. ACTINIUM

Actinium is radioactive with no biological role.

90. THORIUM

Decay of Thorium-232 (along with Uranium-238) provides significant heat to the Earth's interior today. This radiogenic heating keeps the Earth's core molten, enabling the geodynamo that generates Earth's magnetic field. This magnetic field protects the planet and its atmosphere from solar wind, preventing atmospheric stripping and shielding life from harmful cosmic radiation. It also drives plate tectonics and volcanic activity.

91. PROTACTINIUM

Protactinium is radioactive with no biological role.

92. URANIUM

The decay of Uranium-238 is one of the principal sources of heat in the Earth's core today (along with Thorium-232 and potassium-40). Uranium-235 was a more significant heat source in the early Earth due to its shorter half-life.

This radiogenic heating keeps the Earth's core molten, enabling a persistent magnetic field that protects the planet and its atmosphere from solar wind. This protection has been essential for maintaining Earth's atmosphere and water over geological time. Uranium decay also provides volcanic and tectonic activity that recycles nutrients and creates diverse habitats.

Interestingly, **some bacteria can use uranium in anaerobic respiration**, reducing U(VI) to U(IV), representing an actual biological utilisation of uranium beyond its geophysical roles [38].

Uranium is the heaviest naturally occurring element in significant abundance.

93+. TRANSURANICS

Elements heavier than uranium (neptunium and beyond) are either not naturally occurring or exist only in trace amounts from nuclear decay. None have biological roles.

SUMMARY

Essential Elements by Category

Major structural elements (6): H, C, N, O, P, S

Major minerals (4): Na, Mg, K, Ca

Essential trace elements for most life (15): B, F (beneficial), Cl, Mn, Fe, Co, Cu, Zn, Se, Br, I, and in some organisms: V, Cr (debated), Ni, Mo

Taxon-essential elements:

- **Si** - essential for diatoms and many sponges
- **Lanthanides (La, Ce, Nd, etc.)** - essential for methylotrophic bacteria
- **Cd** - essential for some marine diatoms (when Zn is scarce)

- **W** - essential for some archaea and bacteria

Elements with Non-Biological Roles Supporting Life

- **He** - stellar nucleosynthesis, alpha decay
- **Al, Si** - Earth's crust substrate (though Si also has biological roles)
- **Fe** - Earth's core and magnetic field
- **K, Th, U** - radiogenic heating of Earth's core, magnetic field maintenance

Elements with Minimal or No Biological Role

Noble gases: He, Ne, Ar, Kr, Xe, Rn

Post-transition metals: Ga, Ge, In, Sn, Sb, Pb, Bi, Tl

Platinum group: Ru, Rh, Pd, Os, Ir, Pt, Au

Group 3 transition metals: Sc, Y

Radioactive elements: Tc, Po, At, Fr, Ra, Ac, Pa, and all transuranics

Elements with toxicity but no function: Be, As (except in some bacteria), Hg (except in some bacteria), most heavy metals

Updated Count

At least 36 elements are now known to have direct biochemical roles in at least some organisms:

- 6 major structural (C, H, N, O, P, S)
- 4 major minerals (Na, Mg, K, Ca)
- 11 widely essential trace elements (B, Cl, Mn, Fe, Co, Cu, Zn, Se, Br, I, Mo)
- 4 essential in specific taxa (V, Ni, Si, W)
- 8+ lanthanides (La, Ce, Nd, and others) essential for methylotrophs
- 2 specialised marine roles (Cd, Sr)
- 1 element with debated status (Cr)

This represents a significant expansion from the original estimate of 31 elements, primarily due to recent discoveries of lanthanide-utilising microbes, bromine essentiality in animals, silicon requirements in diatoms, and cadmium use in marine diatoms.

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