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Nitrogen, a Builder of Life

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Abstract

Nitrogen, named after the Greek word nitron, is a colorless, odorless, tasteless, and relatively inert gas. It is the fifth most abundant element in the universe and, on Earth, one of the most widely distributed elements across the lithosphere, atmosphere, hydrosphere, and biosphere. For millennia, nitrogen - present in organic materials - was unknowingly used as a fertilizer for crops, long before its identity as a chemical element was understood. Scientific developments beginning in the seventeenth century, and accelerating particularly during the nineteenth century, paved the way for a deeper understanding of nitrogen and its fundamental role in sustaining life on this planet. Nitrogen is a constituent of many inorganic materials used in everyday life and, more importantly, of essential organic compounds such as DNA, proteins, and chlorophyll, which form the basis of all living organisms. This paper presents a brief exploration of the nature of nitrogen, its discovery, its applications, and its role in some of the most important components of living matter.

Keywords: *Nitrogen cycle, DNA, Amino acids, Proteins, Chlorophyl*

Resumo

Nitrogénio, palavra derivada do Grego nitron, é um gás inerte, sem cor, cheiro ou sabor. O nitrogénio é o quinto mais abundante elemento no universo e na Terra é um dos mais abundantes na litosfera, atmosfera, hidrosfera e biosfera. O nitrogénio na forma de materiais orgânicos foi usado por milénios como fertilizante de cultivos, mas as pessoas desse tempo não sabiam da sua existência nem de qualquer outro elemento químico. Os desenvolvimentos científicos a partir do século 17, particularmente no século 19, abriram caminho para se compreender o que é o nitrogénio e o seu papel na vida deste planeta. O nitrogénio é o constituinte de muitos materiais inorgânicos que usamos na nossa vida diária e, mais importante, é constituinte de compostos orgânicos como o ADN, proteínas e clorofila que fazem parte de organismos vivos. Este artigo é uma curta viagem sobre a natureza do nitrogénio, a sua descoberta, o seu uso e o seu papel em alguns dos mais importantes constituintes de toda a matéria viva

Palavras-chave: *Ciclo do Nitrogénio, ADN, Amino ácidos, Proteínas, Clorofila*

1 – Nitrogen. Definition, Properties, Occurrence

Nitrogen derives its name from the Greek words *nitron*, referring to native soda, and genes, meaning “forming.” Nitrogen (symbol N) is a nonmetallic element belonging to Group 15 of the periodic table. It is a colorless, odorless, and tasteless gas that naturally exists as diatomic molecules (N_2), its only naturally occurring allotrope. Molecular nitrogen is remarkably inert due to the presence of a triple covalent bond - comprising three shared pairs of electrons - between the two nitrogen atoms. This bond, with an energy of nearly 1000 $kJ \cdot mol^{-1}$, is among the strongest known in nature. The combination of this strong triple bond and the molecule’s lack of polarity accounts for nitrogen’s low chemical reactivity. Nitrogen has two stable isotopes, ^{14}N and ^{15}N, of which ^{14}N is by far the most abundant, accounting for approximately 99.636% of natural nitrogen.

Nitrogen is the fifth most abundant element in the universe, and on Earth it is widely distributed throughout the lithosphere, atmosphere, hydrosphere, and biosphere. The lithosphere contains approximately 94% of Earth's nitrogen, primarily in the form of nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+), while about 6% is found in the atmosphere as nitrogen oxides (e.g., NO and N_2O) and molecular nitrogen (N_2). Only trace amounts (approximately 0.006%) occur in the hydrosphere and biosphere, mainly as NO_3^-, NO_2^-, and NH_4^+ (Ye, Tian, & Jin, 2022). Free nitrogen is also found in many meteorites, in volcanic and m ine gases, in certain mineral springs, and in extraterrestrial environments such as the Sun, as well as some stars and nebulae.

On Earth, nitrogen also occurs in mineral deposits such as niter, or saltpeter (potassium nitrate, KNO_3), and Chile saltpeter (sodium nitrate, $NaNO_3$). Another nitrogen-rich material is guano, which accumulates in bat caves and in arid regions frequented by birds. In combined forms, nitrogen is present in rainwater and soils primarily as ammonia and ammonium salts, and in seawater as ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-) ions. Nitrogen constitutes, on average, approximately 16 percent by weight of the complex organic compounds known as proteins. The natural abundance of nitrogen in Earth's crust is about 0.3 parts per 1,000. On a cosmic scale, the estimated total abundance of nitrogen in the universe ranges from three to seven atoms per atom of silicon, which is conventionally used as a reference standard.

2 – Nitrogen. History

In 1675, the English writer and diarist John Evelyn (1620–1706) was the first to note that rainwater was not pure, but instead contained a substance he termed "celestial nitre." Later, in 1699, Woodward demonstrated through experimentation that the River Thames contained compounds other than water (Radojević & Harrison, 1992; Woodward, 1699).

In 1772, Carl Wilhelm Scheele (1742–1786), a German-Swedish pharmaceutical chemist, showed that air is a mixture of two gases: one that supports combustion, which he called "fire air" and another remaining after combustion, which he termed "foul air" (Scheele, Forster, & Kirwan, 1780).

Nitrogen was officially discovered in 1772 by the Scottish scientist Daniel Rutherford (1749–1818), who was the first to publish his experimental findings. At the same time, however, Carl Scheele, Henry Cavendish, Joseph Priestley, and others were also investigating what was then known as "burnt" or "dephlogisticated air" referring to air devoid of oxygen. Antoine-Laurent Lavoisier later named this gas azote, meaning "no life," in reference to its inert nature. The term nitrogen was introduced in 1790 by the French chemist Jean-Antoine-Claude Chaptal (1756–1832), who originally called it *nitrogène*, a reference to *nitre* (potassium nitrate), a substance known to contain nitrogen (Prasad & Shivay, 2021).

Following its discovery in the eighteenth century, the nineteenth century saw major advances in understanding how nitrogen is transformed from one chemical species to another. During this period, scientific discussions surrounding nitrogen were largely focused on its essential role in plant growth:

- The need of crop N fertilization.
- The N balance of N on soils cultivated with legumes.
- If N fertilization is necessary, how to provide N fertilizer when natural deposits of N are unavailable or exhausted.

The relationship between fertilizers and plant growth was first empirically observed by Bernard Palissy (c. 1510–c. 1590), a French potter, scientist, and naturalist. In 1563, he concluded that plants utilize substances present in the soil and that, consequently, soils must be replenished with manure and other amendments to promote plant growth. Palissy referred to the substances extracted by plants from the soil as “salts” (Galloway, Leach, Bleeker, & Erisman, 2013).

Justus Freiherr von Liebig (1803–1873), a German scientist who made major contributions to chemistry as well as to agricultural and biological chemistry, argued in his influential 1840 work *Die organische Chemie in ihrer Anwendung auf Agricultur und Physiologie* (“Organic Chemistry in Its Application to Agriculture and Physiology”) that, during the decomposition of organic matter, nitrogen escapes into the atmosphere in the form of ammonia, which is subsequently returned to the soil through precipitation and becomes available to plants (Klein, 2020). Liebig’s thesis - that atmospheric ammonia constituted the sole source of nitrogen for plants - implied that nitrogen fertilization was both unnecessary and inexhaustible, since it was the atmosphere, rather than the soil, that supplied nitrogen to vegetation (Böhm & Wissemeier, 2025).

Liebig’s assertion was strongly opposed in England by John Bennet Lawes (1814–1900), founder of the world’s first agricultural research station at Rothamsted, and by his colleague Joseph Henry Gilbert (1817–1901), who had obtained his doctorate in chemistry under Liebig in Giessen in 1840. Based on their long-term experiments at Rothamsted, Lawes and Gilbert demonstrated that high grain yields could be achieved only when sufficient plant-available nitrogen was present in the soil. Liebig, however, countered these findings by casting doubt on the methodology and scientific validity of the Rothamsted field trials (Böhm & Wissemeier, 2025; Russeli, 1942). Over time, the results of the Rothamsted experiments gained wide recognition among other scientists, including Julius Adolph Stöckhardt (1809–1886), a German agricultural chemist at Hohenheim, who clearly stated in 1851 that traditional manure fertilization of arable soils was insufficient to eliminate nitrogen deficiency (Stöckhardt, 1851).

Nitrogen is abundant in the atmosphere, yet it is largely inaccessible to most organisms because it exists in an inert molecular form. Although it is a crucial nutrient for plant growth and development, most plants lack the enzymes required to utilize

atmospheric nitrogen directly and therefore depend on biological nitrogen fixation by microorganisms.

For thousands of years, farmers observed that legumes such as peas and soybeans enhanced the growth of other crops, including wheat. The Greeks and Romans recognized the benefits of cultivating legumes for improving crop productivity, although the underlying mechanisms remained unknown (White, 1970). Nineteenth-century research subsequently revealed that legumes, through symbiosis with nitrogen-fixing bacteria, convert atmospheric nitrogen (N_2) into ammonium (NH_3), a form that can be assimilated by plants.

Biological nitrogen fixation (BNF) was first demonstrated by Jean-Baptiste Boussingault (1802–1887) in 1838 (Boussingault, 1838). Subsequently, the German agricultural chemist Hermann Hellriegel (1831–1895) showed that leguminous plants acquire atmospheric nitrogen through a process later termed nitrogen fixation, which occurs in specialized nodules on their roots (Hellriegel & Wilfarth, 1888). Martinus Willem Beijerinck (1851–1931), a Dutch microbiologist and botanist, later established that these root nodules contain bacteria, which he named Rhizobium (rhizobia), and demonstrated that these microorganisms carry out the biochemical reactions responsible for nitrogen fixation. Beijerinck's work provided a classic example of symbiosis between plants and bacteria: the rhizobia supply fixed nitrogen to the legume host, while the plant provides the bacteria with a protected environment and a source of nutrients (Iterson, Jong, & Kluyver, 2013).

BNF also occurs naturally in soils through the activity of free-living and associative nitrogen-fixing microorganisms, including Azotobacter, Azospirillum, and cyanobacteria, as well as symbiotically in legume root nodules by Rhizobium. All known nitrogen-fixing organisms, collectively referred to as diazotrophs, are prokaryotes. Their capacity to fix atmospheric nitrogen depends on the nitrogenase enzyme system, which catalyzes the reduction of dinitrogen (N_2) to ammonia at an energetic cost of approximately 16 ATP molecules per N_2 molecule fixed, as expressed in the following equation (Einsle & Rees, 2020)

$$N_2 + 16ATP + 16H_2O + 8e^- \rightarrow 2NH_3 + H_2 + 16ADP + 16Pi \qquad [1]$$

The enzyme nitrogenase present in bacteria breaks the triple covalent bond of N2 to add three hydrogen atoms to each nitrogen atom to form NH3. The energy for transferring electrons comes from the hydrolysis of ATP. There are three types of BNF:

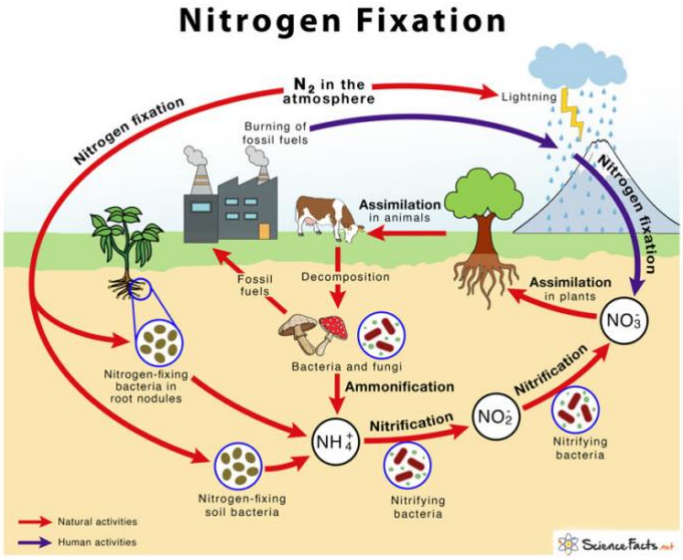
- Symbiotic nitrogen fixation. This is the process found by Hermann Hellriegel. Besides the symbiosis between *Rhizobium* or *Bradyrhizobium* with legumes, there are other cases like water fern Azolla with the cyanobacterium Anabaena azollae and actinorhizal trees and shrubs, such as Alder, with the actinomycete Frankia (Kumar, Singh, Kumari, Kumar, & Yadav, 2024).

- Associative nitrogen fixation. There is a close association between the microorganisms and the plants such as bacterial genera like Azospirillum, Agrobacterium, Arthrobacter, and Flavobacterium with cereal crops such as rice, wheat, potato, tomato and corn (Van Dommelen & Vanderleyden, 2007).

- Nitrogen fixation by free-living heterotrophs. Soil-living heterotrophic bacteria, deriving energy from the decomposition of organic molecules performed by other organisms, fix nitrogen independently without associating with any other organism (Smercina, Evans, Friesen, & Tiemann, 2019). Ammonia produced from organically bound nitrogen is called ammonification (Ingole & Burghate, 2014).

In figure 1 it is depicted the place of nitrogen fixation within the nitrogen cycle.

Figure 1: Nitrogen cycle and nitrogen fixation



(https://www.sciencefacts.net/nitrogen-fixation.html)

The nitrogen cycle comprises a series of processes that transform nitrogen among its various chemical forms within the environment. Nitrogen fixation is one of these processes and involves the conversion of atmospheric nitrogen gas (N_2) into ammonia (NH_3). Ammonia is subsequently oxidized to nitrite (NO_2^-) and then to nitrate (NO_3^-) through nitrification, a process carried out exclusively by prokaryotes and occurring predominantly under aerobic conditions. Nitrification is a two-step process mediated by specialized microorganisms: in the first step, ammonia-oxidizing microbes convert ammonia to nitrite via the intermediate hydroxylamine [2][3]

$$NH_3 + O_2 + 2e^- \rightarrow NH_2OH + H_2O \quad [2]$$

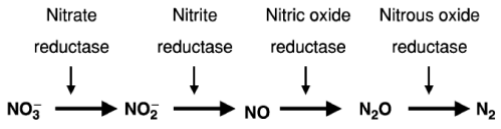
$$NH_2OH + H_2O \rightarrow NO_2^- + 5H^+ + 4e^- \quad [3]$$

Aerobic ammonia oxidizers are autotrophs using ammonia as the energy source instead of light. There are ammonia-oxidizing Archaea and bacteria in the genera *Nitrosomonas*, *Nitrosospira*, and *Nitrosococcus* (Könneke et al., 2005).

The second step in nitrification is the oxidation of nitrite (NO2-) to nitrate (NO3-) carried out by nitrate-oxidizing bacteria, also autotrophs, of the genera *Nitrospira*, *Nitrobacter*, *Nitrococcus*, and *Nitrospina* [4]

$$2NO_2^- + O_2 \rightarrow NO_3^- \qquad [4]$$

Denitrification returns N2 to the atmosphere, closing the cycle. Denitrification is a microbial mediated process that reduces sequentially nitrogen oxides (NO3-, NO2-) to N gases (NO, N2O) and then to N2; each of these steps are carried out by the following enzymes nitrate reductase, nitrite reductase, nitric oxide reductase, and nitrous oxide reductase [5] (Martens, 2005)



[5]

The equation of the entire process is

$$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O \qquad [6]$$

Denitrification is primarily carried out by facultative anaerobic heterotrophs - including Pseudomonas, Escherichia, Enterobacter, Micrococcus, Rhizobium, and Bacillus - that inhabit anaerobic environments. When oxygen becomes depleted, these organisms use nitrate rather than oxygen as the terminal electron acceptor during respiration. Such conditions are commonly found in warm, waterlogged soils, groundwater, oil reservoirs, and marine sediments. Some autotrophic bacteria, such as *Thiobacillus denitrificans*, *Alcaligenes eutropha*, and *Paracoccus denitrificans*, as well as certain archaea, including *Halobacterium marismortui*, also possess denitrification capabilities (Mothapo et al., 2015).

Denitrification plays a crucial environmental role by maintaining balance within the nitrogen cycle. It counteracts the accumulation of inorganic nitrogen compounds that are directly usable only by microorganisms and plants, upon which animals ultimately depend for their nitrogen supply.

In addition to biological processes, nitrogen fixation also occurs naturally through lightning, which represents the primary abiotic source of fixed nitrogen. The energy released by lightning breaks atmospheric molecular nitrogen into reactive nitrogen oxides, which subsequently react with water to form nitrous and nitric acids (Raymond, Siefert, Staples, & Blankenship, 2004).

Research conducted by numerous scientists during the nineteenth century established that fertilization was essential for achieving high crop yields. At the time, the primary fertilizers were organic, such as manure; however, growing agricultural demand soon exceeded their availability, prompting the search for alternative sources. In 1802, the German geographer, naturalist, and explorer Alexander von Humboldt (1769–1859) introduced guano samples from Peru to Europe. Guano - bird excrement rich in nitrogen and phosphorus - had been used as a fertilizer by local populations for centuries. In 1841, the first shipment of Peruvian guano arrived in Great Britain, and its commercialization rapidly expanded across Western Europe and the United States. As guano reserves declined, they were replaced by other South American resources, notably nitrate deposits from the Atacama Desert in Chile, as well as by ammonium sulfate, a by-product of the coal industry (Strotmann, Herment, & Page, 2021).

By the late nineteenth and early twentieth centuries, natural fertilizer sources had become increasingly scarce as guano and Chilean nitrate deposits were depleted. In 1909, Fritz Haber and Robert Le Rossignol developed a method for synthesizing ammonia, which was later industrially scaled by Carl Bosch and his colleagues at the German company BASF. This effort culminated in the opening of the first commercial ammonia synthesis plant in 1913 at Oppau, near Ludwigshafen (Rouwenhorst, Travis, & Lefferts, 2022). The synthesis of ammonia (NH_3) from relatively unreactive atmospheric nitrogen (N_2) and hydrogen (H_2), known as the Haber–Bosch process, is widely regarded by historians as one of the most significant scientific and technological developments in human history.

$$3H_2 + N_2 \Leftrightarrow 2NH_3 \qquad \text{with DHr} = -46 \text{ kJ mol-}NH_3^{-1} \qquad [7]$$

Fritz Haber was awarded the Nobel Prize in Chemistry in 1918 for the synthesis of ammonia, while Carl Bosch received the prize in 1931 for his related contributions to high-pressure chemistry. The Haber–Bosch process represented a major technological breakthrough, enabling the large-scale production of synthetic nitrogen fertilizers. Today, this process produces approximately 170 million tons of ammonia annually worldwide, with about 80% used for fertilizer production (Crow, 2023), Ammonia is also used in refrigeration and in the manufacture of explosives. However, the process is highly energy-intensive, consuming an estimated 1–2% of global energy production and accounting for 1–3% of total CO_2 emissions (Song, Basheer, & Zare, 2023).

The most common nitrogen fertilizers include ammonium sulfate ($(NH_4)_2SO_4$), ammonium nitrate (NH_4NO_3), ammonium chloride (NH_4Cl), and urea ($CO(NH_2)_2$). Over time, global agriculture has shifted from nitrogen scarcity to overabundance, leading to excessive fertilizer use and a range of undesirable environmental consequences.

Rising global food demand has intensified pressure to increase crop productivity, driving continued growth in nitrogen fertilizer use. Currently, more than 110 Tg of

nitrogen fertilizer are applied annually worldwide (Schroeder et al., 2013). Excessive fertilizer inputs, combined with inefficient fertilization practices, have resulted in low nitrogen use efficiency. Notably, nitrogen fertilizer application has increased three times faster than crop productivity, indicating a decline in crops' ability to use nitrogen efficiently (Hirel, Tétu, Lea, & Dubois, 2011). This inefficiency represents a serious concern, as it contributes to increased production costs and exacerbates food insecurity (Salembier, Segrestin, Berthet, Weil, & Meynard, 2018).

An estimated 50–70% of applied nitrogen fertilizer is lost to the environment, causing significant ecological damage. These losses contribute to soil acidification, eutrophication of surface waters (Kissel, Bock, & Ogles, 2020), and nitrate (NO_3^-) contamination of surface and groundwater. Additionally, fertilizers such as ammonium sulfate can degrade soil quality, while nitrogen oxides and ammonium (NH_4^+) emissions contribute to air pollution (Ward, 2009). Some nitrogen is also released as nitrous oxide (N_2O), a potent greenhouse gas that contributes to ozone layer depletion and climate change (Prasad & Shivay, 2021).

3 – Nitrogen. A Structural Nutrient

Nitrogen (N) is the fourth most prevalent element in the biosphere, after oxygen, carbon, and hydrogen, and is an essential component of total biomass (Sparacino-Watkins, Stolz, & Basu, 2014). It is a fundamental constituent of both plant and animal tissues and is required for DNA synthesis, protein production, chlorophyll formation, and the biosynthesis of numerous nitrogenous compounds. These compounds support a wide range of animal functions - including hormonal regulation, immune responses, neurotransmission, and antioxidant defenses - as well as key plant processes such as photosynthesis, water and nutrient uptake, flowering time regulation, and responses to abiotic stress (Tessari, 2006; Zayed et al., 2023).

Many fundamental concepts in biology were established during the second half of the nineteenth century, paving the way for critical discoveries in the twentieth century.

- The basics of evolution theory was laid out by Charles Darwin (1809-1882) and Alfred Wallace (1823-1913) in 1858 (Darwin & Wallace, 1858) and in 1859 Darwin published his book On the Origin of the Species by Means of Natural Selection (Darwin, 1859).
- In 1865 Gregor Mendel (1822-1884) discovered the laws of heredity (Rheinberger, 2020).
- In 1868/9 the Swiss physician and biologist Friedrich Miescher (1844-1895), working at the University of Tübingen, performed experiments on the chemical composition of leukocytes that lead to the discovery of DNA (Dahm, 2005).
- In 1882 Walter Flemming (1843-1905) discovered chromosomes, which are later found to contain DNA (Paweletz, 2001).
- In 1902 – 1904 it was created the theory, later confirmed, that genes are located in the chromosomes of the cell nucleus by the German biologist Theodor Boveri (1862-

1915) and the American geneticist and physician Walter Sutton (1877-1916) (Portin, 2014).

- 1952, Rosalind Franklin (1920-1958) uses X-ray crystallography to create images of DNA (Maddox, 2003).

- 1953, James Watson (1928-) and Francis Crick (1916-2004) discover the structure of DNA, which is the double helix that we know today (Watson & Crick, 1953).

- 1990, The Human Genome Project begins, which was an international research effort to map out the entire human genome; the first draft of the human genome was completed in 2000 (Roberts, 2001).

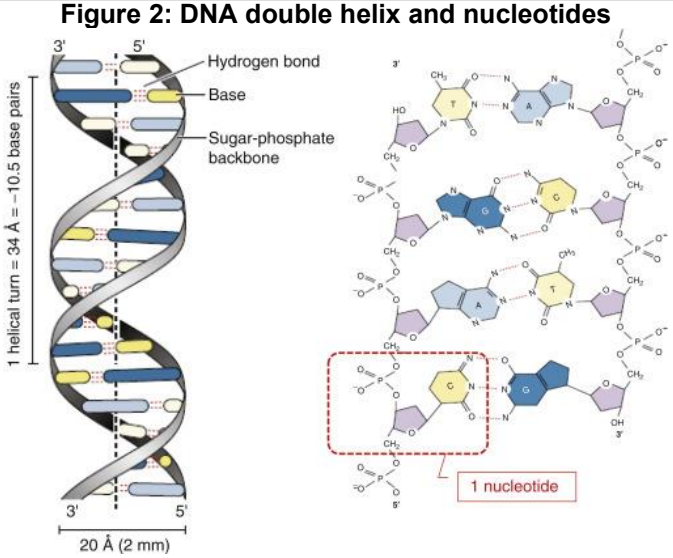
3.1 – Nucleic Acids

Nucleic acids are macromolecules that store and transmit a cell's genetic information and provide the instructions necessary for cellular function, making them essential for the continuity of life. The two principal types of nucleic acids are deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). DNA serves as the genetic material of all living organisms and is located in the nucleus of eukaryotic cells, as well as in organelles such as mitochondria and chloroplasts. In prokaryotic organisms, DNA is not enclosed within a membrane-bound nucleus.

The complete genetic complement of an organism is known as its genome. In eukaryotic cells, DNA associates with histone proteins to form chromatin, which constitutes the structural material of eukaryotic chromosomes. Each chromosome may contain thousands of genes, many of which encode proteins, while others encode functional RNA molecules. RNA, the second major type of nucleic acid, plays a central role in protein synthesis.

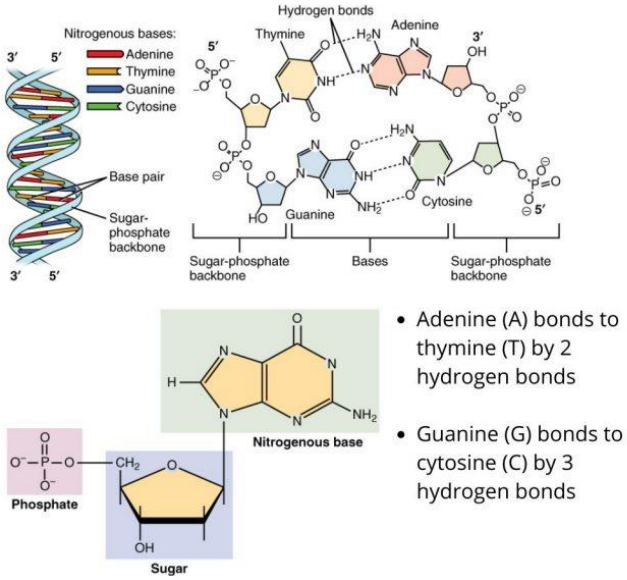
DNA has a characteristic double-helical structure, formed by two single strands twisted around each other (Fig. 2). Each strand consists of a long chain of repeating subunits called nucleotides. Every nucleotide is composed of three components: a five-carbon sugar (deoxyribose), a phosphate group, and one of four nitrogenous bases - adenine, guanine, cytosine, or thymine (Fig. 3) (Bano, Fradetal, Ollivier, Choi, & Stambouli, 2016).

Figure 2: DNA double helix and nucleotides



(Bano et al., 2016)

Figure 3: Three parts nucleotides of DNA



(https://sciencenotes.org/wp-content/uploads/2020/11/Nucleotides-in-DNA-768x640.jpg)

Nitrogen is a fundamental component of the nitrogenous bases of DNA - adenine, thymine, cytosine, and guanine - which are essential for the synthesis, structural integrity, and proper function of DNA. Consequently, nitrogen is a primary nutrient required by all life on Earth (Shen, 2019). Beyond its role in nucleic acids, nitrogen is also a vital constituent of proteins.

3.2 - Proteins

Proteins are large, complex macromolecules that perform a wide range of essential functions in all living organisms. They carry out most cellular activities and

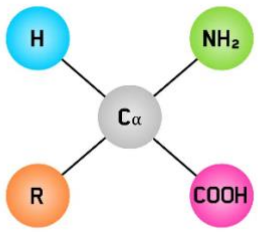
are required for the structure, function, and regulation of the body's tissues and organs. Contemporary knowledge of proteins is the result of pioneering work by early scientists who laid the foundation for modern biochemistry.

In 1789, the French chemist Antoine Fourcroy (1755–1809) first recognized several types of proteins, which he referred to as "albumins" or *Eiweisskörper* (Smeaton, 1955). Later, in 1838, Jöns Jakob Berzelius (1779–1848) coined the term "protein," derived from the Greek word *proteios* ("primary" or "of first importance") (Carpenter, 2000). Around the same time, the Dutch chemist Gerardus Mulder (1802–1880) performed elemental analyses of proteins and, in 1837, proposed that they shared a common core substance (Stenesh, 1998). During the 19th century, proteins were widely believed to be the primary nutrients responsible for forming the body's structural components.

A major breakthrough in protein research occurred in 1949, when Frederick Sanger (1918–2013) determined the first complete amino acid sequence of a protein, insulin. This achievement earned him the Nobel Prize in Chemistry in 1958. Further advances in understanding protein structure were made by Christian Anfinsen (1916–1995), whose studies on ribonuclease A demonstrated the relationship between amino acid sequence and protein folding, leading to his Nobel Prize in 1972.

Proteins are composed of hundreds of smaller units called amino acids, which are commonly found in plants and animals. These amino acids are linked together by peptide bonds to form long chains known as polypeptides. The type, number, and sequence of amino acids in a polypeptide determine the protein's unique three-dimensional structure and, consequently, its specific biological function. Amino acids are organic compounds that contain both an amine ($–NH_2$) group and a carboxyl (–COOH) group, as well as a distinctive side chain (R group) attached to a central carbon atom (Fig. 4). The chemical properties of the R group are responsible for the diversity of amino acids and the wide range of protein structures and functions. (Khan, Siddiqi, & Salahuddin, 2017).

Figure 4: Basic structure of amino acid

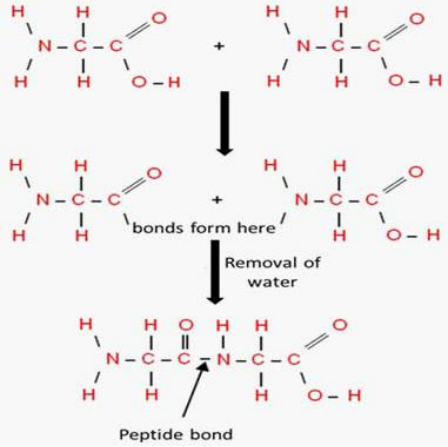


(https://www.bachem.com/articles/peptides/what-are-amino-acids/)

Individual amino acids link together to form polypeptides through peptide bonds, also known as amide bonds. A peptide bond is a covalent bond formed between the

carboxyl group (–COOH) of one amino acid and the amino group ($–NH_2$) of another amino acid, as illustrated in Fig. 5 (Khan et al., 2017)

Figure 5: Formation of peptide bond



(Khan et al., 2017)

The formation of polypeptides and their subsequent transformation into functional proteins are determined by the sequence of genes encoded in DNA. This process, known as protein synthesis, is a fundamental biological mechanism that occurs in all living organisms.

Protein synthesis takes place in two main stages: transcription and translation. Transcription involves the transfer of genetic information from DNA to messenger RNA (mRNA) and occurs in the nucleus. Translation occurs at the ribosome - the cellular “protein factory - which is composed of ribosomal RNA (rRNA) and proteins. During transcription, DNA serves as a template for the synthesis of an mRNA molecule. The newly formed mRNA then exits the nucleus through a nuclear pore and travels to the ribosome, where translation takes place. At the ribosome, the genetic code carried by the mRNA is read and used to direct the synthesis of a polypeptide chain. Following synthesis, the polypeptide may undergo additional processing to produce a mature, functional protein (Raj, 2023).

The newly synthesized polypeptide chain undergoes one or more post-translational modifications (Khan et al., 2017) including:

- Proteolysis: the proteins get cleaved, that is, their N-terminal, C-terminal, or the internal amino-acid residues are removed from the polypeptide by the action of proteases.
- Protein folding: the nascent proteins get folded to achieve the secondary and tertiary structures.

After these modifications, proteins may associate with other polypeptides or with different types of molecules, such as lipids or carbohydrates, forming complexes such

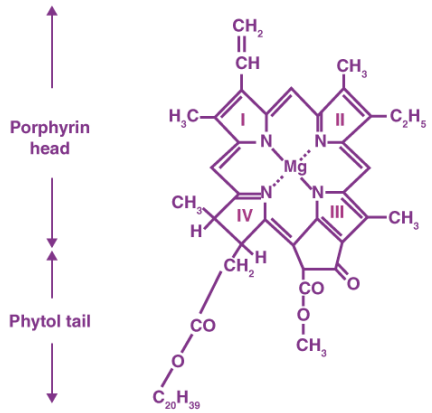
as lipoproteins or glycoproteins. Many proteins are subsequently transported to the Golgi apparatus, where they undergo further modification and sorting according to their specific cellular functions.

3.3 - Chlorophyl

Chlorophyll is a complex nitrogen-containing molecule composed of a porphyrin ring with a centrally coordinated magnesium ion surrounded by four nitrogen atoms. Attached to this ring is a long hydrophobic tail made of carbon and hydrogen atoms, which anchors the molecule within the chloroplast membrane (Fig. 6) (Melkozernov & Blankenship, 2007). Its empirical formula is

$C_{55}H_{72}MgN_4O_5$ [8]

Figure 6: Structure of chlorophyl



(https://byjus.com/biology/chlorophyll-structure/)

Chlorophyll is not a single molecule; rather, at least six distinct forms are known, differing in the side groups attached to the porphyrin ring. The structure shown in Fig. 6 corresponds to chlorophyll a, often referred to as the “universal” chlorophyll because it is found in nearly all photosynthetic organisms. Chlorophyll occurs in plants, algae, and cyanobacteria (Pareek et al., 2017). The term chlorophyll originates from the Greek words *khloros*, meaning green, and *phyllon*, meaning leaf.

Chlorophyll was first isolated and named in 1817 by the French chemists Joseph Bienaimé Caventou (1795–1877) and Pierre Pelletier (1788–1842). In 1883, the German physiologist Julius von Sachs (1832–1897) demonstrated that chlorophyll is localized within specialized cellular structures known as chloroplasts. Between 1906 and 1914, the German scientist Richard Willstätter (1872–1942) purified chlorophyll a and b and discovered that a magnesium ion occupies the center of the chlorophyll molecule—work that earned him the Nobel Prize in Chemistry in 1915. Later, in 1965, the American chemist Robert Woodward (1917–1979) received the Nobel Prize in Chemistry for elucidating the detailed molecular structure of chlorophyll (Govindjee, Stirbet, Lindsey, & Scheer, 2024).

Chlorophyll plays a central role in photosynthesis, the process by which photoautotrophic organisms use light energy to synthesize organic compounds. When chlorophyll absorbs sunlight, it captures light energy and converts it into chemical energy, driving the conversion of carbon dioxide and water into glucose and oxygen.

$$6CO_2 + 6H_2O \xrightarrow[\text{Chlorophyl}]{\text{Light}} C_6H_{12}O_6 + 6O_2 \qquad [9]$$

Chlorophyll is a vital pigment that plays several crucial roles in the environment ecological balance and the sustenance of life on Earth:

- Energy Production. The glucose produced during photosynthesis serves as an energy source used for growth, reproduction, and other vital functions of organisms that contribute to the food chain and overall ecosystem balance, supporting a wide range of animal life, including our own.
- Oxygen Production. During photosynthesis, chlorophyll helps release oxygen into the atmosphere as a byproduct, which is essential for the survival of most living organisms.

Chlorophyll is green because it absorbs light wavelengths in the blue and red regions of the spectrum that are required for photosynthesis and reflects the green wavelength, which is not used, to produce the intense green color of plants (Pareek et al., 2017).

4 – Concluding remarks

Nitrogen is a fundamental component of nearly all biological molecules, making it indispensable to life on this planet. Since its scientific discovery, humans have learned how to synthesize nitrogen compounds and apply them in everyday life—most notably in agricultural fertilizers, which are now essential for producing sufficient food for a rapidly growing global population. However, large-scale nitrogen production and use have significantly altered the natural nitrogen cycle, leading to a range of harmful environmental consequences. Addressing and mitigating the pollution resulting from these alterations now requires continued scientific research and responsible management.

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