Nitrogen, a Builder of Life

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Abstract

Nitrogen, named after the Greek word *nitron* is a colorless, odorless, tasteless, inert gas. Nitrogen is the fifth most abundant element in the universe and on Earth is among the most widely distributed elements in the lithosphere, atmosphere, hydrosphere, and biosphere. Nitrogen in the form of organic materials was used for millenniums as a fertilizer of crops but people of that time did not know about it any other chemical element for that matter. Scientific developments from the 17^{th} century onward, but particularly in 19^{th} century, opened the way to understand nitrogen and its role on the life of this planet. Nitrogen is a constituent of many inorganic materials we use on our daily life and, most crucial, of organic composts such as DNA, proteins, and chlorophyl that make up living organisms. This paper is a short voyage over nitrogen nature, its discovery, its use and its role in some the most important constituents of all living matter.

Keywords: *History, 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: História, Ciclo do Nitrogénio, ADN, Amino ácidos, Proteínas, Clorofila

1 – Nitrogen. Definition, Properties, Occurrence

Nitrogen was named after the Greek word *nitron*, for native soda, and *genes* for forming. Nitrogen, symbol N, is a nonmetallic element of Group 15 of the periodic table. It is a colorless, odorless, tasteless gas that exists in the form of diatomic molecules, N2 its sole natural allotrope. The gas is inert due to a triple covalent bond, three pair of shared electrons, between the two nitrogen atoms that is one of the strongest found in nature (bond energy of nearly 1000 kJ/mol). Due to the strength of its triple bond and lack of polarity, it is very inert. It has two isotopes: N^{14} and N^{15} but N^{14} is 99.636% more abundant than N^{15}. Nitrogen is the fifth most abundant element in the universe and on Earth N is among the most widely distributed elements in the lithosphere, atmosphere, hydrosphere, and biosphere. The lithosphere contains 94% of all nitrogen on Earth (e.g., NO_3^-, NO_2^-, and NH_4^+), with the remaining 6% in the atmosphere (e.g., NO, N_2O, and N_2) and a trace (0.006%) in the hydrosphere and biosphere (e.g., NO_3^-, NO_2^-, and NH_4^+) (Ye, Tian, & Jin, 2022). Free nitrogen is found in many meteorites, in gases of volcanoes, mines, and some mineral springs, in the Sun and in some stars and nebulae.

In Earth, nitrogen also occurs in mineral deposits of niter or saltpeter (potassium nitrate, KNO_3) and Chile saltpeter (sodium nitrate, $NaNO_3$). Another material rich in nitrogen is guano, found in bat caves and in dry places frequented by birds. In combination, nitrogen is found in the rain and soil as ammonia and ammonium salts and in seawater as ammonium (NH_4^+), nitrite ($NO_2^−$), and nitrate ($NO_3^−$) ions. Nitrogen constitutes on the average about 16 percent by weight of the complex organic compounds known as proteins. The natural abundance of nitrogen in Earth's crust is 0.3 part per 1,000. The cosmic abundance - the estimated total abundance in the universe - is between three and seven atoms per atom of silicon, which is taken as the standard.

2 – Nitrogen. History

In 1675 John Evelyn (1620–1706), English writer and diarist, made the first notation that rainwater was not pure but contained a material, which he termed "celestial nitre", and Woodward in 1699 proved through experimentation that there were compounds in the Thames River other than water (Radojević & Harrison, 1992; Woodward, 1699).

Carl Wilhelm Scheele (1742-1786), a German Swedish pharmaceutical chemist, showed in 1772 that air is a mixture of two gases, one of which he called "fire air," because it supported combustion, and the other "foul air," because it was left after the "fire air" had been used up (Scheele, Forster, & Kirwan, 1780).

Nitrogen was officially discovered in 1772 by Scottish scientist Daniel Rutherford (1749-1818) who was the first to publish his experimental results but at the same time however, Carl Scheele, Henry Cavendish, Joseph Priestley and others were investigating "burnt or dephlogisticated air", as air without oxygen was then called. Antoine Laurent Lavoisier called it azote, meaning "no-life", because it is inert. The name "nitrogen" was coined in 1790 by French chemist Jean Antoine Claude Chaptal (1756-1832) who originally named it "nitrogene", a reference to nitre (potassium nitrate), which was known to contain nitrogen (Prasad & Shivay, 2021).

After its discovery in the eighteenth century, in the nineteenth century it was discovered how N was transformed from one species to another and the discussions around nitrogen at that time were largely centered on its need for plants:

- 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 relation 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 use products that are in the soil, thus soil must be replenished with manure and other products to promote plant growth. Palissy referred to the products that plant extract 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, in his famous work *Die organische Chemie in ihrer Anwendung auf Agricultur und Physiologie* (“Organic Chemistry in its Application to Agriculture and Physiology”) from 1840 (Klein, 2020), asserted that from decomposition of organic matter nitrogen escapes into the atmosphere in the form of ammonia which is returned to the soil with the precipitation and it is then available to the plants. Liebig’s thesis of ammonia in the air as the sole source of nitrogen for plants made N fertilization unnecessary and inexhaustible because it is not the soil but the atmosphere that supplies the nitrogen to the vegetation (Böhm & Wissemeier, 2025).

Liebig´s assertion was strongly opposed in England by John Bennet Lawes (1814–1900), founder of the first agricultural research station of the world in Rothamsted, and his colleague Joseph Henry Gilbert (1817–1901), who obtained his doctorate in chemistry from Liebig in Giessen in 1840. Lawes and Gilbert, based on their experiments at Rothamsted, reported that high yield of grains could only be achieved if there was sufficient plant available nitrogen in the soil but Liebig counteracted casting doubts about the methodology of the Rothamsted field trials and their scientific validity (Böhm & Wissemeier, 2025; Russeli, 1942). Rothamsted tests results ended up being recognized by many other scientists among them Julius Adolph Stöckhardt (1809-1886), a German agricultural chemist, in Hohenheim who clearly pointed out in 1851 that traditional manure fertilization of arable soils was not sufficient to eliminate a nitrogen deficiency (Stöckhardt, 1851).

Nitrogen is abundant in the atmosphere but is largely inaccessible to most organisms due to its inert form. It is a crucial nutrient for plant growth and development but most plants lack the enzymes required to make use of atmospheric nitrogen directly, instead, they rely on nitrogen fixation by bacteria.

For thousands of years farmers were aware that plants like peas and soy beans promoted growth of other plants such as wheat. Greeks and Romans were aware of the benefits of growing legumes to the productivity of their crops but they did not know why (White, 1970). Research done in the 19thcentury discovered how legumes converted N_2 into ammonium (NH_3) which can be used by plants.

Biological fixation of nitrogen (BNF) was discovered by Jean-Baptiste Boussingault (1802-1887) in 1838 (Boussingault, 1838). Later, Hermann Hellriegel (1831-1895), a German agricultural chemist, found out that leguminous plants took atmospheric nitrogen through the process known as nitrogen fixation in the nodules of the legume’s roots (Hellriegel & Wilfarth, 1888). Martinus Willem Beijerinck (1851–1931), a Dutch microbiologist and botanist, discovered that the root nodules contained bacteria, which he named rhizobia, and these rhizobia perform the biochemical reaction of nitrogen fixation. Beijerinck was also responsible for the discovery of a classic example of symbiosis between plants and bacteria, the bacteria in the root nodules provide nitrogen for legume plant, while the rhizobia depend on the root nodules as an environment to grow and a source of nutrition (Iterson, Jong, & Kluyver, 2013).

BNF occurs naturally in the soil by different nitrogen-fixing bacteria such as *Azotobacter*, *Azospirillum*, and *Cyanobacteria* and, as mentioned above, in the nodules of legume's roots by *Rhizobium*. All known nitrogen-fixing organisms (diazatrophs) are prokaryotes, and the capacity for nitrogen fixation in these organisms relies solely upon the nitrogenase enzyme system at 16 ATPs hydrolyzed per N_2 fixed, expressed in the following equation (Einsle & Rees, 2020)

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

The enzyme nitrogenase present in bacteria breaks the triple covalent bond of N_2 to add three hydrogen atoms to each nitrogen atom to form NH_3. 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.

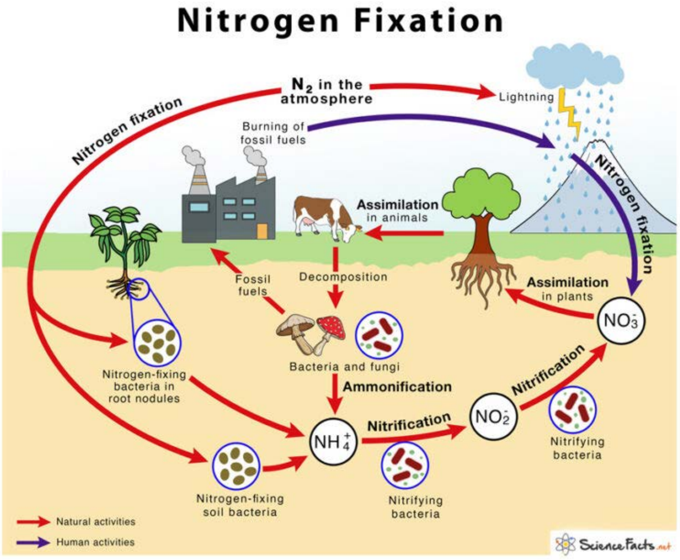


Fig.1 - Nitrogen cycle and nitrogen fixation (https://www.sciencefacts.net/nitrogen-fixation.html)

The nitrogen cycle is a series of processes that converts nitrogen in various forms through the environment and nitrogen fixation is one of the processes in this cycle. Nitrogen fixation turns nitrogen gas (N_2) into ammonia (NH_3) which is converted to nitrites (NO_2) and nitrates (NO_3) by nitrification that is carried out exclusively by prokaryotes and occurs mostly aerobically. Nitrification is a two-step process with intervention of microbes known as ammonia oxidizers that in the first step convert ammonia to nitrate via the intermediate hydroxylamine [2][3]

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

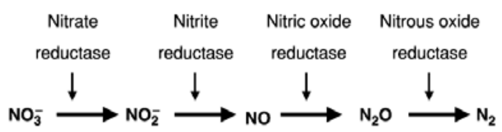
$$NH_2OH + H_2O \rightarrow NO_2^- + 5H^+ + 4e^- \qquad [3]$$

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 (NO_2^-) to nitrate (NO_3^-) 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 N_2 to the atmosphere, closing the cycle. Denitrification is a microbial mediated process that reduces sequentially nitrogen oxides (NO_3^-, NO_2^-) to N gases (NO, N_2O) and then to N_2; 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

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

Denitrification is mostly performed by facultative anaerobes - *Pseudomonas, Escherichia, Enterobacter, Micrococcus, Rhizobium, Bacillus* - heterotrophs in anaerobic environments when depleted oxygen force them to use nitrate, instead of oxygen, for terminal electron acceptor during respiration. Such environment is found in warm and wet soils, groundwater, oil reservoirs, and sea floors. Some autotrophs, like *Thiobacillus denitrificans*, *Alcaligenes eutropha*, *Paracoccus denitrificans* and archaeal like *Halobacterium marismortui* have denitrification capability (Mothapo et al., 2015). Denitrification has an important environmental role as it keeps the cycle in balance where it is clear the dominance of inorganic molecules of N that only microorganisms and plants can use, animals depend on them for their own supply of nitrogen.

Other naturally occurring N fixation is done by lightning the primary abiotic source of fixed nitrogen. Energy from lightning breaks atmospheric molecular nitrogen into nitrous oxide which reacts with water to form nitrous acid or nitric acid (Raymond, Siefert, Staples, & Blankenship, 2004).

The research done by many scientists in 19th century made it clear that fertilization was necessary to obtain large yielding crops. At that time, the primary fertilizers were organic as manure but the demand exceeded the availability and other sources were procured. In 1802 the German geographer, naturalist and traveler Alexander von Humboldt (1769-1859) brought to Europe samples of guano from Peru. The bird dung guano, containing nitrogen and phosphorus, was used as fertilizer by local people for centuries. In 1841, the first shipment of Peruvian guano arrived in Great Britain and its commercialization rapidly spread in Western Europe and the United States. As the stocks of guano dwindle it was replaced by another South American commodity, nitrates found in the Atacama Desert in Chile and by sulphate of ammonia, a by-product of the coal industry (Strotmann, Herment, & Page, 2021).

Late in 19th century and early 20th century there was a scarcity of natural fertilizers as the deposits of guano and Chilean nitrates were exhausted. In 1909, Fritz Haber and Robert Le Rossignol invented a method to synthesis ammonia and it was scaled up by Carl Bosch and colleagues at the German firm BASF, which opened the first commercial plant in 1913 at Oppau, near its Ludwigshafen works (Rouwenhorst, Travis, & Lefferts, 2022). The synthesis of ammonia (NH_3) from unreactive nitrogen (N_2) and hydrogen (H_2) [7] known as the Haber–Bosch process, is considered by many historians one of the most significant scientific–technical developments in human history.

$$3H_2 + N_2 \Leftrightarrow 2NH_3 \quad \text{with DHr} = -46\ \text{kJ mol-NH}_3^{-1} \qquad [7]$$

Haber was awarded the Nobel Prize in Chemistry in 1918 for ammonia synthesis and Bosch in 1931 for related contributions to high-pressure chemistry.

Haber–Bosch process was a technological breakthrough that enabled the production of synthetic N fertilizers on a large scale. This process produces globally around 170 million tons of ammonia every year with approximately 80% used in fertilizers (Crow, 2023), it also used in refrigeration and making explosives, it consumes 1–2% of the total global energy production and emits 1–3% of total CO_2 emissions (Song, Basheer, & Zare, 2023).

Most of nitrogen fertilizers are ammonium sulphate - $(NH_4)2SO_4$, ammonium nitrate - NH_4NO_3, ammonium chloride - NH_4Cl, and urea - $CO(NH_2)_2$. The world went from scarcity to overabundance to the point of excessive use in agriculture with a host of undesirable effects.

The global food demands increase the pressure to achieve higher crop productions and the global demand for agricultural N fertilizer continues to escalate; actually, more than 110 Tg of N fertilizer is applied annually (Schroeder et al., 2013). The excessive input of N fertilizer and inadequate methods of fertilization result in low N use efficiency as the N fertilizer application has increased 3 times faster than the crop productivity, indicating that crops have been reduced in their ability to use N efficiently (Hirel, Tétu, Lea, & Dubois, 2011), a serious problem because it drives up food insecurity (Salembier, Segrestin, Berthet, Weil, & Meynard, 2018). About 50 to 70% of the applied N fertilizer is lost to the environment, causing serious problems, such as soil acidification, eutrophication of water bodies (Kissel, Bock, & Ogles, 2020), NO_3^- pollutes superficial and groundwater, ammonium sulfate causes soil pollution, nitrogen oxides and NH_4^+ cause air pollution (Ward, 2009). Some N is lost as nitrous oxide (N_2O), which is responsible for the depletion of the ozone layer in the earth's atmosphere (Prasad & Shivay, 2021).

3 – Nitrogen. A Structural Nutrient

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). Nitrogen is a main body component of both plants and animals and is required for DNA, protein synthesis, chlorophyl and the production of several nitrogenous compounds involved in a variety of animal functions (hormones, immune mediators, neurotransmitters, antioxidant defenses, etc.) and plant functions (photosynthesis, water and nutrient intake, flowering time, abiotic stress response, etc.) (Tessari, 2006; Zayed et al., 2023).

Many fundamental concepts in biology were established in the second half of the 19th century that opened the way to critical discoveries of the 20th 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 carry the genetic code of a cell and instructions for the its functioning which makes them essential for the continuity of life. The two main types of nucleic acids are deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). DNA is the genetic material in all living organisms and it is found in the nucleus of eukaryotes and in the organelles, chloroplasts, and mitochondria. In prokaryotes, the DNA is not enclosed in a nucleus.

The entire genetic content is known as its genome. In eukaryotic cells, DNA forms a complex with histone proteins to form chromatin, the substance of eukaryotic chromosomes. A chromosome may contain thousands of genes many of them with the information to make protein products and other genes code for RNA products. The other type of nucleic acid, RNA, is mostly involved in protein synthesis.

The DNA structure can be perceived as a double helical structure where two single DNA strands twisted around each other in the form of a double helix (Fig. 2). Each DNA strands consist of a long chain of repeating subunits which are called nucleotides. The nucleotides are composed of three parts: a five-carbon cycle sugar, named ribose, a phosphate group, and a nitrogenous nucleobase (adenine, guanine, cytosine, and thymine) (Fig. 3) (Bano, Fradetal, Ollivier, Choi, & Stambouli, 2016).

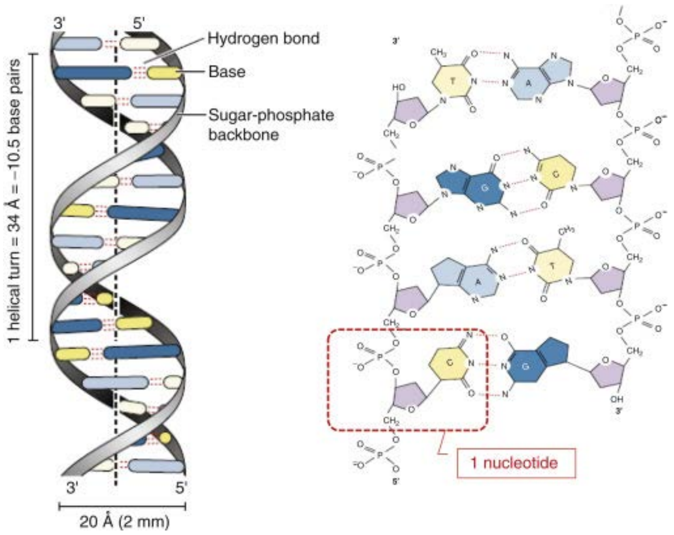


Fig. 2 – DNA double helix and nucleotides (Bano et al., 2016)

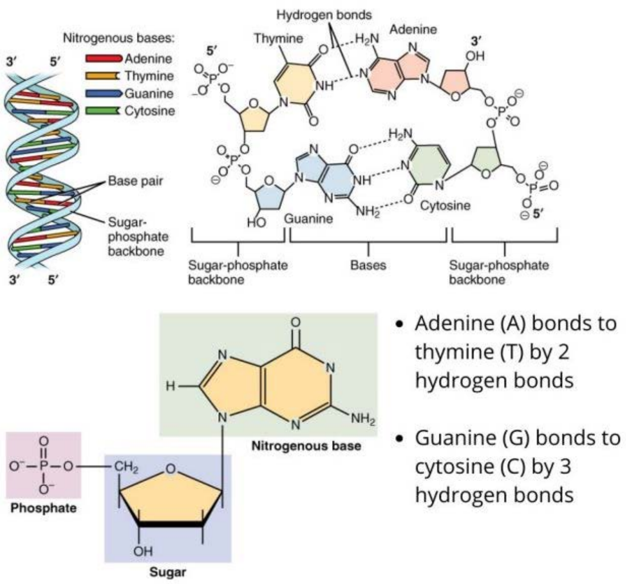


Fig. 3 – Three parts nucleotides of DNA (https://sciencenotes.org/wp-content/uploads/2020/11/Nucleotides-in-DNA-768x640.jpg)

Nitrogen is present in nitrogenous bases of DNA, which include adenine, thymine, cytosine, and guanine. These nitrogenous bases are essential for the synthesis, structure and function of DNA and that makes nitrogen a primary nutrient for all life on Earth (Shen, 2019). The essential nitrogen is also present in proteins.

3.2 - Proteins

Proteins are large, complex macromolecules that perform a wide range of functions in all living organisms. They do most of the work in cells and are required for the structure, function, regulation of the body's tissues and organs. Today knowledge and discoveries about proteins is possible by the pioneer work of earlier scientists. In 1789 the French chemist Antoine Fourcroy (1755-1809) first recognized several types of proteins, then called "albumins" or "Eiweisskörper" (Smeaton, 1955). Jöns Berzelius (1779-1848) coined the term “proteins” in 1838, a term derived from the Greek word *proteios* (“primary”) (Carpenter, 2000). Dutch chemist Gerardus Mulder (1802-1880) performed an elemental analysis of proteins and in 1837 recognized that they have a single common core substance (Stenesh, 1998). In the 19th century, scientists believed that protein itself was the key nutrient for forming the body’s structure. The first amino acid sequence for a protein was obtained by Frederick Sanger (1918-2013) in 1949 for insulin which earned him the Nobel Prize in 1958. Christian Anfinsen (1916-1995) researched into the structure of proteins, specifically ribonuclease A, that brought him the Nobel Prize in 1972.

Proteins are made up of hundreds of smaller units called amino acids commonly found in plants and animals, which are attached together by peptide bond to one another in long chains called polypeptides. There are many different types of amino acids that can be combined to make a protein and the number and sequence of amino acids determines each protein’s unique 3-dimensional structure and its specific function.

Amino acids are organic compounds that contain amine ($-NH_2$) and Carboxyl (-COOH) functional groups, along with a side-chain (R group) that is specific for each amino acid attached to a central carbon atom (Fig. 4) (Khan, Siddiqi, & Salahuddin, 2017)

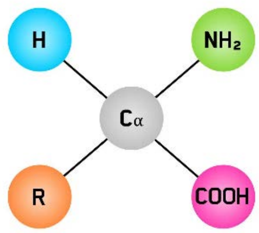


Fig. 4 – Basic structure of amino acid (https://www.bachem.com/articles/peptides/what-are-amino-acids/)

Individual amino acids link together to form polypeptides thru peptide bonds, also known as amide bond, that are defined as a covalent bond between the carbonyl group (COOH) of one amino acid and the imino group (H) of another amino acid, exemplified in fig. 5 (Khan et al., 2017)

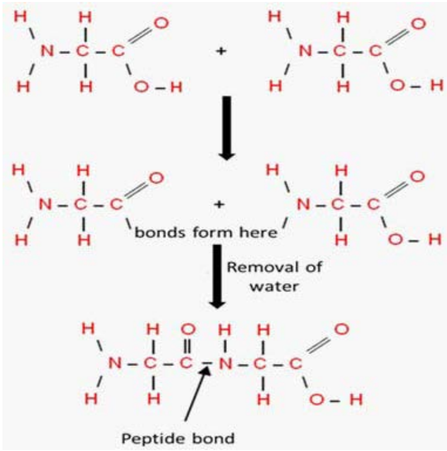


Fig. 5 - Formation of peptide bond (Khan et al., 2017)

The formation of polypeptides and their posterior transformation that will end up as proteins is determined by the sequence of genes existing in DNA. This process is called protein synthesis and is a fundamental biological process that occurs in all living organisms.

Protein synthesis occurs in two stages: transcription and translation. Transcription is the transfer of genetic instructions in DNA to mRNA in the nucleus. Translation occurs at the ribosome (the protein factory), which consists of rRNA and proteins. In the first step (transcription), DNA is used as a template to make a messenger RNA molecule (mRNA). The mRNA thus formed, exits the nucleus through a nuclear pore and travels to the ribosome for the next step (translation). Upon reaching the ribosome, the genetic code in RNA is read and used for polypeptide synthesis. After a polypeptide chain is synthesized, it may undergo additional processing to form the finished protein (Raj, 2023).

The newly formed polypeptide chain undergoes either one of the two post-translational modifications (Khan et al., 2017):

- 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, the protein may bind with other polypeptides or with different types of molecules, such as lipids or carbohydrates, forming lipoproteins or glycoproteins, respectively. Many proteins travel to the Golgi apparatus where they are further modified according to their role in cell.

3.3 - Chlorophyl

Chlorophyll is another complex nitrogenous molecule with a structure that has a ring called a “porphyrin ring”, which contains magnesium at its center surrounded by four nitrogen atoms, and a long “tail” made of carbon and hydrogen atoms, helping it stay anchored in the chloroplast membranes (Fig. 6) (Melkozernov & Blankenship, 2007). Its empirical formula is

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

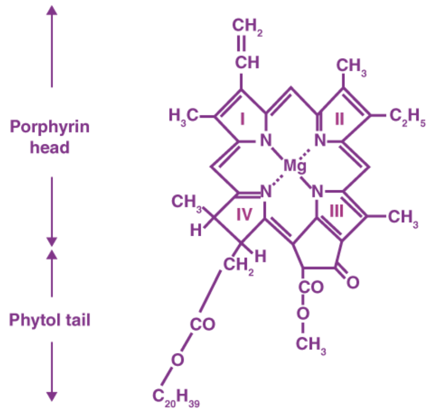


Fig. 6 – Structure of chlorophyl (https://byjus.com/biology/chlorophyll-structure/)

Chlorophyll is not a single molecule, there are at least six varieties that have various side groups on the rings and the structure shown in Fig. 6 is of **chlorophyll a** called the "universal" chlorophyll because it is present in almost all photosynthetic organisms. Chlorophyll is found in plants, algae and cyanobacteria (Pareek et al., 2017). The word "chlorophyll" comes from the Greek words *khloros* meaning green, and *phyllon* meaning leaves

Chlorophyll was first isolated and named by Joseph Bienaimé Caventou (1795-1877) and Pierre Pelletier (1788-1842) in 1817. In 1883, German physiologist Julius von Sachs (1832-1897) showed that chlorophyll is found in special structures called chloroplasts. Chlorophyll **a** and **b** were purified by German scientist Richard Willstatter (1872-1942) in 1906-1914 and he discovered that Mg is at the center of the chlorophyl molecule; his work was awarded with the Nobel Prize in Chemistry in 1915. In 1965, an American scientist, Robert Woodward (1917-1979), won a Noble Prize in Chemistry for figuring out the structure of the chlorophyll molecule (Govindjee, Stirbet, Lindsey, & Scheer, 2024).

Chlorophyll plays a crucial role in photosynthesis which is how autotroph organisms that use light as energy source make their own food. When sunlight hits chlorophyll, it captures the light energy and uses it to turn carbon dioxide and water into glucose and oxygen.

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

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 present in almost any constituent matter of living organisms making it indispensable to life in this planet. Since it was discovered by science, we have learned how to synthetized it and to apply it to uses in everyday life, one of the most important is agricultural fertilizers now essential to produce enough food to an increasing world population. Our production and use of nitrogen has altered its environmental cycle with some deleterious effects that now we have to use science to address them and solve the pollution we are responsible for.

5 - References

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