Nitrogen fixation

Biological

Biological nitrogen fixation (BNF) occurs when atmospheric nitrogen is converted to ammonia by a nitrogenase enzyme.[1] The overall reaction for BNF is:

$$N_2 + 16ATP + 16H_2O + 8e^- + 8H^+ \rightarrow 2NH_3 + H_2 + 16ADP + 16P_i$$

The process is coupled to the hydrolysis of 16 equivalents of ATP and is accompanied by the co-formation of one equivalent of H_2.[14] The conversion of N_2 into ammonia occurs at a metal cluster called FeMoco, an abbreviation for the iron-molybdenum cofactor. The mechanism proceeds via a series of protonation and reduction steps wherein the FeMoco active site hydrogenates the N_2 substrate.[15] In free-living diazotrophs, nitrogenase-generated ammonia is assimilated into glutamate through the glutamine synthetase/glutamate synthase pathway. The microbial nif genes required for nitrogen fixation are widely distributed in diverse environments.[16]

For example, decomposing wood, which generally has a low nitrogen content, has been shown to host a diazotrophic community.[17][18] The bacteria enrich the wood substrate with nitrogen through fixation, thus enabling deadwood decomposition by fungi.[19]

Nitrogenases are rapidly degraded by oxygen. For this reason, many bacteria cease production of the enzyme in the presence of oxygen. Many nitrogen-fixing organisms exist only in anaerobic conditions, respiring to draw down oxygen levels, or binding the oxygen with a protein such as leghemoglobin.[20][21]

Importance of nitrogen

Atmospheric nitrogen is inaccessible to most organisms,[22] because its triple covalent bond is very strong. Most take up fixed nitrogen from various sources. For every 100 atoms of carbon, roughly 2 to 20 atoms of nitrogen are assimilated. The atomic ratio of carbon (C) : nitrogen (N) : phosphorus (P) observed on average in planktonic biomass was originally described by Alfred Redfield,[23] who determined the stoichiometric relationship between C:N:P atoms, The Redfield Ratio, to be 106:16:1.[23]

Nitrogenase

The protein complex nitrogenase is responsible for catalyzing the reduction of nitrogen gas (N_2) to ammonia (NH_3).[24][25] In cyanobacteria, this enzyme system is housed in a specialized cell called the heterocyst.[26] The production of the nitrogenase complex is genetically regulated, and the activity of the protein complex is dependent on ambient oxygen concentrations, and intra- and extracellular concentrations of ammonia and oxidized nitrogen species (nitrate and nitrite).[27][28][29] Additionally, the combined concentrations of both ammonium and nitrate are thought to inhibit N_{Fix}, specifically when intracellular concentrations of 2-oxoglutarate (2-OG) exceed a critical threshold.[30] The specialized heterocyst cell is necessary for the performance of nitrogenase as a result of its sensitivity to ambient oxygen.[31]

Nitrogenase consist of two proteins, a catalytic iron-dependent protein, commonly referred to as MoFe protein

In 1901, Beijerinck showed that *Azotobacter chroococcum* was able to fix atmospheric nitrogen. This was the first species of the *azotobacter* genus, so-named by him. It is also the first known diazotroph, species that use diatomic nitrogen as a step in the complete nitrogen cycle.

Biological

Biological nitrogen fixation (BNF) occurs when atmospheric nitrogen is converted to ammonia by a nitrogenase enzyme.[1] The overall reaction for BNF is:

$$N_2 + 16ATP + 16H_2O + 8e^- + 8H^+ \rightarrow 2NH_3 + H_2 + 16ADP + 16P_i$$

The process is coupled to the hydrolysis of 16 equivalents of ATP and is accompanied by the co-formation of one equivalent of H_2.[14] The conversion of N_2 into ammonia occurs at a metal cluster called FeMoco, an abbreviation for the iron-molybdenum cofactor. The mechanism proceeds via a series of protonation and reduction steps wherein the FeMoco active site hydrogenates the N_2 substrate.[15] In free-living diazotrophs, nitrogenase-generated ammonia is assimilated into glutamate through the glutamine synthetase/glutamate synthase pathway. The microbial nif genes required for nitrogen fixation are widely distributed in diverse environments.[16]

For example, decomposing wood, which generally has a low nitrogen content, has been shown to host a diazotrophic community.[17][18] The bacteria enrich the wood substrate with nitrogen through fixation, thus enabling deadwood decomposition by fungi.[19]

Nitrogenases are rapidly degraded by oxygen. For this reason, many bacteria cease production of the enzyme in the presence of oxygen. Many nitrogen-fixing organisms exist only in anaerobic conditions, respiring to draw down oxygen levels, or binding the oxygen with a protein such as leghemoglobin.[20][21]

Importance of nitrogen

Atmospheric nitrogen is inaccessible to most organisms,[22] because its triple covalent bond is very strong. Most take up fixed nitrogen from various sources. For every 100 atoms of carbon, roughly 2 to 20 atoms of nitrogen are assimilated. The atomic ratio of carbon (C) : nitrogen (N) : phosphorus (P) observed on average in planktonic biomass was originally described by Alfred Redfield,[23] who determined the stoichiometric relationship between C:N:P atoms, The Redfield Ratio, to be 106:16:1.[23]

Nitrogenase

The protein complex nitrogenase is responsible for catalyzing the reduction of nitrogen gas (N_2) to ammonia (NH_3).[24][25] In cyanobacteria, this enzyme system is housed in a specialized cell called the heterocyst.[26] The production of the nitrogenase complex is genetically regulated, and the activity of the protein complex is dependent on ambient oxygen concentrations, and intra- and extracellular concentrations of ammonia and oxidized nitrogen species (nitrate and nitrite).[27][28][29] Additionally, the combined concentrations of both ammonium and nitrate are thought to inhibit N_{Fix}, specifically when intracellular concentrations of 2-oxoglutarate (2-OG) exceed a critical threshold.[30] The specialized heterocyst cell is necessary for the performance of nitrogenase as a result of its sensitivity to ambient oxygen.[31]

Nitrogenase consist of two proteins, a catalytic iron-dependent protein, commonly referred to as MoFe protein and a reducing iron-only protein (Fe protein). There are three different iron dependent proteins, molybdenum-dependent, vanadium-dependent, and iron-only, with all three nitrogenase protein variations containing an iron protein component. Molybdenum-dependent nitrogenase is the most commonly present nitrogenase.[32] The

different types of nitrogenase can be determined by the specific iron protein component.[33] Nitrogenase is highly conserved. Gene expression through DNA sequencing can distinguish which protein complex is present in the microorganism and potentially being expressed. Most frequently, the *nif*H gene is used to identify the presence of molybdenum-dependent nitrogenase, followed by closely related nitrogenase reductases (component II) *vnf*H and *anf*H representing vanadium-dependent and iron-only nitrogenase, respectively.[34] In studying the ecology and evolution of nitrogen-fixing bacteria, the *nifH* gene is the biomarker most widely used.[35] *nif*H has two similar genes *anf*H and vnfH that also encode for the nitrogenase reductase component of the nitrogenase complex.[36]

Evolution of Nitrogenase

Nitrogenase is thought to have evolved sometime between 1.5-2.2 billion years ago (Ga),[37][38] although some isotopic support showing nitrogenase evolution as early as around 3.2 Ga.[39] Nitrogenase appears to have evolved from maturase-like proteins, although the function of the preceding protein is currently unknown.[40]

Nitrogenase has three different forms (*Nif, Anf, and Vnf*) that correspond with the metal found in the active site of the protein (Molybdenum, Iron, and Vanadium respectively).[41] Marine metal abundances over Earth's geologic timeline are thought to have driven the relative abundance of which form of nitrogenase was most common.[42] Currently, there is no conclusive agreement on which form of nitrogenase arose first.

Microorganisms

Diazotrophs are widespread within domain Bacteria including cyanobacteria (e.g. the highly significant *Trichodesmium* and *Cyanothece*), green sulfur bacteria, purple sulfur bacteria, Azotobacteraceae, rhizobia and *Frankia*.[43][44] Several obligately anaerobic bacteria fix nitrogen including many (but not all) *Clostridium* spp. Some archaea such as *Methanosarcina acetivorans* also fix nitrogen,[45] and several other methanogenic taxa, are significant contributors to nitrogen fixation in oxygen-deficient soils.[46]

Cyanobacteria, commonly known as blue-green algae, inhabit nearly all illuminated environments on Earth and play key roles in the carbon and nitrogen cycle of the biosphere. In general, cyanobacteria can use various inorganic and organic sources of combined nitrogen, such as nitrate, nitrite, ammonium, urea, or some amino acids. Several cyanobacteria strains are also capable of diazotrophic growth, an ability that may have been present in their last common ancestor in the Archean eon.[47] Nitrogen fixation not only naturally occurs in soils but also aquatic systems, including both freshwater and marine.[48][49] Indeed, the amount of nitrogen fixed in the ocean is at least as much as that on land.[50] The colonial marine cyanobacterium *Trichodesmium* is thought to fix nitrogen on such a scale that it accounts for almost half of the nitrogen fixation in marine systems globally.[51] Marine surface lichens and non-photosynthetic bacteria belonging in Proteobacteria and Planctomycetes fixate significant atmospheric nitrogen.[52] Species of nitrogen fixing cyanobacteria in fresh waters include: *Aphanizomenon* and *Dolichospermum* (previously Anabaena).[53] Such species have specialized cells called heterocytes, in which nitrogen fixation occurs via the nitrogenase enzyme.[54][55]

Algae

One type of organelle can turn nitrogen gas into a biologically available form. This nitroplast was discovered in algae.[56]

Root nodule symbioses

Legume family

Plants that contribute to nitrogen fixation include those of the legume family —Fabaceae— with taxa such as kudzu, clover, soybean, alfalfa, lupin, peanut and rooibos.[44] They contain symbiotic rhizobia bacteria within nodules in their root systems, producing nitrogen compounds that help the plant to grow and compete with other plants.[57] When the plant dies, the fixed nitrogen is released, making it available to other plants; this helps to fertilize the soil.[20][58] The great majority of legumes have this association, but a few genera (e.g., *Styphnolobium*) do not. In many traditional farming practices, fields are rotated through various types of crops, which usually include one consisting mainly or entirely of clover.

Nodules are visible on this broad bean root

Fixation efficiency in soil is dependent on many factors, including the legume and air and soil conditions. For example, nitrogen fixation by red clover can range from 50 to 200 lb/acre (56 to 224 kg/ha).[59]

Non-leguminous

The ability to fix nitrogen in nodules is present in actinorhizal plants such as alder and bayberry, with the help of *Frankia* bacteria. They are found in 25 genera in the orders Cucurbitales, Fagales and Rosales, which together with the Fabales form a *nitrogen-fixing clade* of eurosids. The ability to fix nitrogen is not universally present in these families. For example, of 122 Rosaceae genera, only four fix nitrogen. Fabales were the first lineage to branch off this nitrogen-fixing clade; thus, the ability to fix nitrogen may be plesiomorphic and subsequently lost in most descendants of the original nitrogen-fixing plant; however, it may be that the basic genetic and physiological requirements were present in an incipient state in the most recent common ancestors of all these plants, but only evolved to full function in some of them.[60]

A sectioned alder tree root nodule

In addition, *Trema* (*Parasponia*), a tropical genus in the family Cannabaceae, is unusually able to interact with rhizobia and form nitrogen-fixing nodules.[61]

Non-legumious nodulating plants

Family	Genera	Species
Betulaceae	Alnus (alders)	Most or all species
Boraginaceae	Phacelia	Phacelia tanacetifolia
Cannabaceae	Trema (Parasponia)	Trema orientale Trema lamarckiana
Casuarinaceae	Allocasuarina Casuarina Ceuthostoma Gymnostoma	
Coriariaceae	Coriaria	Coriaria arborea Coriaria myrtifolia
Datiscaceae	Datisca	
Elaeagnaceae	Elaeagnus (silverberries) Hippophae (sea-buckthorns) Shepherdia (buffaloberries)	
Myricaceae	Comptonia (sweetfern) Myrica (babyberries)	
Posidoniaceae	Posidonia (seagrass)	
Rhamnaceae	Ceanothus Colletia Discaria Kentrothamnus Retanilla Talguenea Trevoa	
Rosaceae	Cercocarpus (mountain mahoganies) Chamaebatia (mountain miseries) Dryas Purshia/Cowania (bitterbrushes/cliffroses)	

Other plant symbionts

Some other plants live in association with a cyanobiont (cyanobacteria such as *Nostoc*) which fix nitrogen for them:

- Some lichens such as *Lobaria* and *Peltigera*
- Mosquito fern (*Azolla* species)
- Cycads[62]
- *Gunnera*
- *Blasia* (liverwort)
- Hornworts[63]

Some symbiotic relationships involving agriculturally-important plants are:[64]

- Sugarcane and unclear endophytes

- Foxtail millet and *Azospirillum brasilense*
- Kallar grass and *Azoarcus* sp. strain BH72
- Rice and *Herbaspirillum seropedicae*
- Wheat and *Klebsiella pneumoniae*
- Maize landrace 'Sierra Mixe' / 'olotón'[65] and various Bacteroidota and Pseudomonadota

Industrial processes

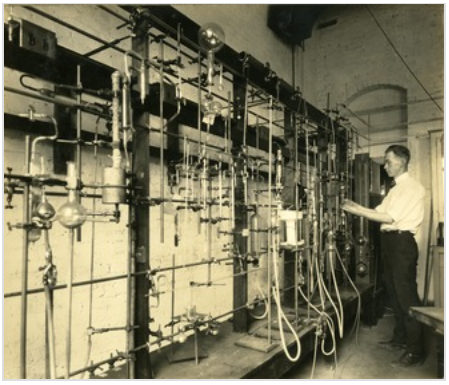
Historical

A method for nitrogen fixation was first described by Henry Cavendish in 1784 using electric arcs reacting nitrogen and oxygen in air. This method was implemented in the Birkeland–Eyde process of 1903.[66] The fixation of nitrogen by lightning is a very similar natural occurring process.

The possibility that atmospheric nitrogen reacts with certain chemicals was first observed by Desfosses in 1828. He observed that mixtures of alkali metal oxides and carbon react with nitrogen at high temperatures. With the use of barium carbonate as starting material, the first commercial process became available in the 1860s, developed by Margueritte and Sourdeval. The resulting barium cyanide reacts with steam, yielding ammonia. In 1898 Frank and Caro developed what is known as the Frank–Caro process to fix nitrogen in the form of calcium cyanamide. The process was eclipsed by the Haber process, which was discovered in 1909.[67][68]

Haber process

The dominant industrial method for producing ammonia is the Haber process also known as the Haber-Bosch process.[69] Fertilizer production is now the largest source of human-produced fixed nitrogen in the terrestrial ecosystem. Ammonia is a required precursor to fertilizers, explosives, and other products. The Haber process requires high pressures (around 200 atm) and high temperatures (at least 400 °C), which are routine conditions for industrial catalysis. This process uses natural gas as a hydrogen source and air as a nitrogen source. The ammonia product has resulted in an intensification of nitrogen fertilizer globally[70] and is credited with supporting the expansion of the human population from around 2 billion in the early 20th century to roughly 8 billion people now.[71]



Equipment for a study of nitrogen fixation by alpha rays (Fixed Nitrogen Research Laboratory, 1926)

Homogeneous catalysis

Much research has been conducted on the discovery of catalysts for nitrogen fixation, often with the goal of lowering energy requirements. However, such research has thus far failed to approach the efficiency and ease of the Haber process. Many compounds react with atmospheric nitrogen to give dinitrogen complexes. The first dinitrogen complex to be reported was $Ru(NH_3)_5(N_2)^{2+}$.[72] Some soluble complexes do catalyze nitrogen fixation.[73]

Lightning

Nitrogen can be fixed by lightning converting nitrogen gas (N_2) and oxygen gas (O_2) in the atmosphere into NO_x (nitrogen oxides). The N_2 molecule is highly stable and nonreactive due to the triple bond between the nitrogen atoms.[74] Lightning produces enough energy and heat to break this bond[74] allowing nitrogen atoms to react

with oxygen, forming NO_x. These compounds cannot be used by plants, but as this molecule cools, it reacts with oxygen to form NO_2,[75] which in turn reacts with water to produce HNO_2 (nitrous acid) or HNO_3 (nitric acid). When these acids seep into the soil, they make NO_3 (nitrate), which is of use to plants.[76][74]

Lightning heats the air around it in a high-temperature plasma, breaking the bonds of N_2, starting the formation of nitrous acid (HNO_2).

See also

- Birkeland–Eyde process: an industrial fertilizer production process
- Carbon fixation
- Denitrification: an organic process of nitrogen release
- George Washington Carver: an American botanist
- Heterocyst
- Nitrification: biological production of nitrogen
- Nitrogen cycle: the flow and transformation of nitrogen through the environment
- Nitrogen deficiency
- Nitrogen fixation package for quantitative measurement of nitrogen fixation by plants
- Nitrogenase: enzymes used by organisms to fix nitrogen
- Ostwald process: a chemical process for making nitric acid (HNO_3)

References

1. Howard JB, Rees DC (1996). "Structural Basis of Biological Nitrogen Fixation". *Chemical Reviews*. **96** (7): 2965–2982. doi:10.1021/cr9500545 (https://doi.org/10.1021%2Fcr9500545). PMID 11848848 (https://pubmed.ncbi.nlm.nih.gov/11848848).
2. Burris RH, Wilson PW (June 1945). "Biological Nitrogen Fixation". *Annual Review of Biochemistry*. **14** (1): 685–708. doi:10.1146/annurev.bi.14.070145.003345 (https://doi.org/10.1146%2Fannurev.bi.14.070145.003345). ISSN 0066-4154 (https://www.worldcat.org/issn/0066-4154).
3. Wagner SC (2011). "Biological Nitrogen Fixation" (https://www.nature.com/scitable/knowledge/library/biological-nitrogen-fixation-23570419). *Nature Education Knowledge*. **3** (10): 15. Archived (https://web.archive.org/web/20180913194741/http://www.nature.com/scitable/knowledge/library/biological-nitrogen-fixation-23570419) from the original on 13 September 2018. Retrieved 29 January 2019.
4. Zahran HH (December 1999). "Rhizobium-legume symbiosis and nitrogen fixation under severe conditions and in an arid climate" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC98982). *Microbiology and Molecular Biology Reviews*. **63** (4): 968–89, table of contents. doi:10.1128/MMBR.63.4.968-989.1999 (https://doi.org/10.1128%2FMMBR.63.4.968-989.1999). PMC 98982 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC98982). PMID 10585971 (https://pubmed.ncbi.nlm.nih.gov/10585971).
5. Sapountzis P, de Verges J, Rousk K, Cilliers M, Vorster BJ, Poulsen M (2016). "Potential for Nitrogen Fixation in the Fungus-Growing Termite Symbiosis" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5156715). *Frontiers in Microbiology*. **7**: 1993. doi:10.3389/fmicb.2016.01993 (https://doi.org/10.3389%2Ffmicb.2016.01993). PMC 5156715 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5156715). PMID 28018322 (https://pubmed.ncbi.nlm.nih.gov/28018322).
6. Slosson E (1919). *Creative Chemistry* (https://archive.org/details/creativechemist00slosgoog). New York, NY: The Century Co. pp. 19 (https://archive.org/details/creativechemist00slosgoog/page/n42)–37.
7. Hill RD, Rinker RG, Wilson HD (1979). "Atmospheric Nitrogen Fixation by Lightning" (https://doi.org/10.1175%2F1520-0469%281980%29037%3C0179%3AANFBL%3E2.0.CO%3B2). *J. Atmos. Sci.* **37** (1): 179–192. Bibcode:1980JAtS...37..179H (https://ui.adsabs.harvard.edu/abs/1980JAtS...37..179H). doi:10.1175/1520-0469(1980)037<0179:ANFBL>2.0.CO;2 (https://doi.org/10.1175%2F1520-0469%281980%29037%3C0179%3AANFBL%3E2.0.CO%3B2).

8. Boussingault (1838). "Recherches chimiques sur la vegetation, entreprises dans le but d'examiner si les plantes prennent de l'azote à l'atmosphere" (https://babel.hathitrust.org/cgi/pt?id=iau.31858046218297&view=1up&seq=9&skin=2021) [Chemical investigations into vegetation, undertaken with the goal of examining whether plants take up nitrogen in the atmosphere]. *Annales de Chimie et de Physique*. 2nd series (in French). **67**: 5–54. and **69**: 353–367 (https://babel.hathitrust.org/cgi/pt?id=hvd.hx3dx7&view=1up&seq=357&skin=2021).
9. Smil V (2001). *Enriching the Earth*. Massachusetts Institute of Technology.
10. Hellriegel H, Wilfarth H (1888). *Untersuchungen über die Stickstoffnahrung der Gramineen und Leguminosen* (https://www.biodiversitylibrary.org/item/69506#page/7/mode/1up) [*Studies on the nitrogen intake of Gramineae and Leguminosae*] (in German). Berlin, Germany: Buchdruckerei der "Post" Kayssler & Co.
11. Beijerinck MW (1901). "Über oligonitrophile Mikroben" (https://books.google.com/books?id=tcBFAQAAMAAJ&pg=PA561) [On oligonitrophilic microbes]. *Centralblatt für Bakteriologie, Parasitenkunde, Infektionskrankheiten und Hygiene* (in German). **7** (16): 561–582.
12. Howard S. Reed (1942) *A Short History of Plant Science*, page 230, Chronic Publishing
13. Margaret Rossiter (1975) *The Emergence of Agricultural Science*, page 146, Yale University Press
14. Lee CC, Ribbe MW, Hu Y (2014). Kroneck PM, Sosa Torres ME (eds.). "Chapter 7. Cleaving the N,N Triple Bond: The Transformation of Dinitrogen to Ammonia by Nitrogenases". *Metal Ions in Life Sciences*. **14**. Springer: 147–76. doi:10.1007/978-94-017-9269-1_7 (https://doi.org/10.1007%2F978-94-017-9269-1_7). PMID 25416394 (https://pubmed.ncbi.nlm.nih.gov/25416394).
15. Hoffman BM, Lukoyanov D, Dean DR, Seefeldt LC (February 2013). "Nitrogenase: a draft mechanism" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3578145). *Accounts of Chemical Research*. **46** (2): 587–95. doi:10.1021/ar300267m (https://doi.org/10.1021%2Far300267m). PMC 3578145 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3578145). PMID 23289741 (https://pubmed.ncbi.nlm.nih.gov/23289741).
16. Gaby JC, Buckley DH (July 2011). "A global census of nitrogenase diversity". *Environmental Microbiology*. **13** (7): 1790–9. Bibcode:2011EnvMi..13.1790G (https://ui.adsabs.harvard.edu/abs/2011EnvMi..13.1790G). doi:10.1111/j.1462-2920.2011.02488.x (https://doi.org/10.1111%2Fj.1462-2920.2011.02488.x). PMID 21535343 (https://pubmed.ncbi.nlm.nih.gov/21535343).
17. Rinne KT, Rajala T, Peltoniemi K, Chen J, Smolander A, Mäkipää R (2017). "Accumulation rates and sources of external nitrogen in decaying wood in a Norway spruce dominated forest" (https://doi.org/10.1111%2F1365-2435.12734). *Functional Ecology*. **31** (2): 530–541. Bibcode:2017FuEco..31..530R (https://ui.adsabs.harvard.edu/abs/2017FuEco..31..530R). doi:10.1111/1365-2435.12734 (https://doi.org/10.1111%2F1365-2435.12734). ISSN 1365-2435 (https://www.worldcat.org/issn/1365-2435). S2CID 88551895 (https://api.semanticscholar.org/CorpusID:88551895).
18. Hoppe B, Kahl T, Karasch P, Wubet T, Bauhus J, Buscot F, et al. (2014). "Network analysis reveals ecological links between N-fixing bacteria and wood-decaying fungi" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3914916). *PLOS ONE*. **9** (2): e88141. Bibcode:2014PLoSO...988141H (https://ui.adsabs.harvard.edu/abs/2014PLoSO...988141H). doi:10.1371/journal.pone.0088141 (https://doi.org/10.1371%2Fjournal.pone.0088141). PMC 3914916 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3914916). PMID 24505405 (https://pubmed.ncbi.nlm.nih.gov/24505405).
19. Tláskal V, Brabcová V, Větrovský T, Jomura M, López-Mondéjar R, Oliveira Monteiro LM, et al. (January 2021). "Complementary Roles of Wood-Inhabiting Fungi and Bacteria Facilitate Deadwood Decomposition" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7901482). *mSystems*. **6** (1). doi:10.1128/mSystems.01078-20 (https://doi.org/10.1128%2FmSystems.01078-20). PMC 7901482 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7901482). PMID 33436515 (https://pubmed.ncbi.nlm.nih.gov/33436515).
20. Postgate J (1998). *Nitrogen Fixation* (3rd ed.). Cambridge: Cambridge University Press.
21. Streicher SL, Gurney EG, Valentine RC (October 1972). "The nitrogen fixation genes". *Nature*. **239** (5374): 495–9. Bibcode:1972Natur.239..495S (https://ui.adsabs.harvard.edu/abs/1972Natur.239..495S). doi:10.1038/239495a0 (https://doi.org/10.1038%2F239495a0). PMID 4563018 (https://pubmed.ncbi.nlm.nih.gov/4563018). S2CID 4225250 (https://api.semanticscholar.org/CorpusID:4225250).
22. Delwiche CC (1983). "Cycling of Elements in the Biosphere". In Läuchli A, Bieleski RL (eds.). *Inorganic Plant Nutrition*. Encyclopedia of Plant Physiology. Berlin, Heidelberg: Springer. pp. 212–238. doi:10.1007/978-3-642-68885-0_8 (https://doi.org/10.1007%2F978-3-642-68885-0_8). ISBN 978-3-642-68885-0.

23. Redfield AC (1958). "The Biological Control of Chemical Factors in the Environment" (https://www.jstor.org/stable/27827150). *American Scientist*. **46** (3): 230A–221. ISSN 0003-0996 (https://www.worldcat.org/issn/0003-0996). JSTOR 27827150 (https://www.jstor.org/stable/27827150).
24. Seefeldt LC, Yang ZY, Lukoyanov DA, Harris DF, Dean DR, Raugei S, et al. (2020). "Reduction of Substrates by Nitrogenases" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7703680). *Chemical Reviews*. **120** (12): 5082–5106. doi:10.1021/acs.chemrev.9b00556 (https://doi.org/10.1021%2Facs.chemrev.9b00556). PMC 7703680 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7703680). PMID 32176472 (https://pubmed.ncbi.nlm.nih.gov/32176472).
25. Threatt SD, Rees DC (2023). "Biological nitrogen fixation in theory, practice, and reality: A perspective on the molybdenum nitrogenase system" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10100503). *FEBS Letters*. **597** (1): 45–58. doi:10.1002/1873-3468.14534 (https://doi.org/10.1002%2F1873-3468.14534). PMC 10100503 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10100503). PMID 36344435 (https://pubmed.ncbi.nlm.nih.gov/36344435).
26. Peterson RB, Wolk CP (December 1978). "High recovery of nitrogenase activity and of Fe-labeled nitrogenase in heterocysts isolated from Anabaena variabilis" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC393163). *Proceedings of the National Academy of Sciences of the United States of America*. **75** (12): 6271–6275. Bibcode:1978PNAS...75.6271P (https://ui.adsabs.harvard.edu/abs/1978PNAS...75.6271P). doi:10.1073/pnas.75.12.6271 (https://doi.org/10.1073%2Fpnas.75.12.6271). PMC 393163 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC393163). PMID 16592599 (https://pubmed.ncbi.nlm.nih.gov/16592599).
27. Beversdorf LJ, Miller TR, McMahon KD (6 February 2013). "The role of nitrogen fixation in cyanobacterial bloom toxicity in a temperate, eutrophic lake" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3566065). *PLOS ONE*. **8** (2): e56103. Bibcode:2013PLoSO...856103B (https://ui.adsabs.harvard.edu/abs/2013PLoSO...856103B). doi:10.1371/journal.pone.0056103 (https://doi.org/10.1371%2Fjournal.pone.0056103). PMC 3566065 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3566065). PMID 23405255 (https://pubmed.ncbi.nlm.nih.gov/23405255).
28. Gallon JR (1 March 2001). "N2 fixation in phototrophs: adaptation to a specialized way of life". *Plant and Soil*. **230** (1): 39–48. doi:10.1023/A:1004640219659 (https://doi.org/10.1023%2FA%3A1004640219659). ISSN 1573-5036 (https://www.worldcat.org/issn/1573-5036). S2CID 22893775 (https://api.semanticscholar.org/CorpusID:22893775).
29. Paerl H (9 March 2017). "The cyanobacterial nitrogen fixation paradox in natural waters" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5345769). *F1000Research*. **6**: 244. doi:10.12688/f1000research.10603.1 (https://doi.org/10.12688%2Ff1000research.10603.1). PMC 5345769 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5345769). PMID 28357051 (https://pubmed.ncbi.nlm.nih.gov/28357051).
30. Li JH, Laurent S, Konde V, Bédu S, Zhang CC (November 2003). "An increase in the level of 2-oxoglutarate promotes heterocyst development in the cyanobacterium Anabaena sp. strain PCC 7120" (https://doi.org/10.1099%2Fmic.0.26462-0). *Microbiology*. **149** (Pt 11): 3257–3263. doi:10.1099/mic.0.26462-0 (https://doi.org/10.1099%2Fmic.0.26462-0). PMID 14600238 (https://pubmed.ncbi.nlm.nih.gov/14600238).
31. Wolk CP, Ernst A, Elhai J (1994). "Heterocyst Metabolism and Development". In Bryant DA (ed.). *The Molecular Biology of Cyanobacteria*. Advances in Photosynthesis. Dordrecht: Springer Netherlands. pp. 769–823. doi:10.1007/978-94-011-0227-8_27 (https://doi.org/10.1007%2F978-94-011-0227-8_27). ISBN 978-94-011-0227-8.
32. Burgess BK, Lowe DJ (November 1996). "Mechanism of Molybdenum Nitrogenase". *Chemical Reviews*. **96** (7): 2983–3012. doi:10.1021/cr950055x (https://doi.org/10.1021%2Fcr950055x). PMID 11848849 (https://pubmed.ncbi.nlm.nih.gov/11848849).
33. Schneider K, Müller A (2004). "Iron-Only Nitrogenase: Exceptional Catalytic, Structural and Spectroscopic Features". In Smith BE, Richards RL, Newton WE (eds.). *Catalysts for Nitrogen Fixation*. Nitrogen Fixation: Origins, Applications, and Research Progress. Dordrecht: Springer Netherlands. pp. 281–307. doi:10.1007/978-1-4020-3611-8_11 (https://doi.org/10.1007%2F978-1-4020-3611-8_11). ISBN 978-1-4020-3611-8.
34. Knoche KL, Aoyama E, Hasan K, Minteer SD (2017). "Role of Nitrogenase and Ferredoxin in the Mechanism of Bioelectrocatalytic Nitrogen Fixation by the Cyanobacteria Anabaena variabilis SA-1 Mutant Immobilized on Indium Tin Oxide (ITO) Electrodes" (https://www.cheric.org/research/tech/periodicals/view.php?seq=1531452). *Electrochimica Acta* (in Korean). **232**: 396–403. doi:10.1016/j.electacta.2017.02.148 (https://doi.org/10.1016%2Fj.electacta.2017.02.148).

35. Raymond J, Siefert JL, Staples CR, Blankenship RE (March 2004). "The natural history of nitrogen fixation" (https://doi.org/10.1093%2Fmolbev%2Fmsh047). *Molecular Biology and Evolution*. **21** (3): 541–554. doi:10.1093/molbev/msh047 (https://doi.org/10.1093%2Fmolbev%2Fmsh047). PMID 14694078 (https://pubmed.ncbi.nlm.nih.gov/14694078).
36. Schüddekopf K, Hennecke S, Liese U, Kutsche M, Klipp W (May 1993). "Characterization of anf genes specific for the alternative nitrogenase and identification of nif genes required for both nitrogenases in Rhodobacter capsulatus". *Molecular Microbiology*. **8** (4): 673–684. doi:10.1111/j.1365-2958.1993.tb01611.x (https://doi.org/10.1111%2Fj.1365-2958.1993.tb01611.x). PMID 8332060 (https://pubmed.ncbi.nlm.nih.gov/8332060). S2CID 42057860 (https://api.semanticscholar.org/CorpusID:42057860).
37. Garcia AK, McShea H, Kolaczkowski B, Kaçar B (May 2020). "Reconstructing the evolutionary history of nitrogenases: Evidence for ancestral molybdenum-cofactor utilization" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7216921). *Geobiology*. **18** (3): 394–411. Bibcode:2020Gbio...18..394G (https://ui.adsabs.harvard.edu/abs/2020Gbio...18..394G). doi:10.1111/gbi.12381 (https://doi.org/10.1111%2Fgbi.12381). ISSN 1472-4677 (https://www.worldcat.org/issn/1472-4677). PMC 7216921 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7216921). PMID 32065506 (https://pubmed.ncbi.nlm.nih.gov/32065506).
38. Boyd ES, Anbar AD, Miller S, Hamilton TL, Lavin M, Peters JW (May 2011). "A late methanogen origin for molybdenum-dependent nitrogenase" (https://onlinelibrary.wiley.com/doi/10.1111/j.1472-4669.2011.00278.x). *Geobiology*. **9** (3): 221–232. Bibcode:2011Gbio....9..221B (https://ui.adsabs.harvard.edu/abs/2011Gbio....9..221B). doi:10.1111/j.1472-4669.2011.00278.x (https://doi.org/10.1111%2Fj.1472-4669.2011.00278.x). ISSN 1472-4677 (https://www.worldcat.org/issn/1472-4677). PMID 21504537 (https://pubmed.ncbi.nlm.nih.gov/21504537).
39. Stüeken EE, Buick R, Guy BM, Koehler MC (April 2015). "Isotopic evidence for biological nitrogen fixation by molybdenum-nitrogenase from 3.2 Gyr" (https://www.nature.com/articles/nature14180). *Nature*. **520** (7549): 666–669. Bibcode:2015Natur.520..666S (https://ui.adsabs.harvard.edu/abs/2015Natur.520..666S). doi:10.1038/nature14180 (https://doi.org/10.1038%2Fnature14180). ISSN 0028-0836 (https://www.worldcat.org/issn/0028-0836). PMID 25686600 (https://pubmed.ncbi.nlm.nih.gov/25686600).
40. Garcia AK, Kolaczkowski B, Kaçar B (2 March 2022). Archibald J (ed.). "Reconstruction of Nitrogenase Predecessors Suggests Origin from Maturase-Like Proteins" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8890362). *Genome Biology and Evolution*. **14** (3). doi:10.1093/gbe/evac031 (https://doi.org/10.1093%2Fgbe%2Fevac031). ISSN 1759-6653 (https://www.worldcat.org/issn/1759-6653). PMC 8890362 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8890362). PMID 35179578 (https://pubmed.ncbi.nlm.nih.gov/35179578).
41. Eady RR (1 January 1996). "Structure–Function Relationships of Alternative Nitrogenases" (https://pubs.acs.org/doi/10.1021/cr950057h). *Chemical Reviews*. **96** (7): 3013–3030. doi:10.1021/cr950057h (https://doi.org/10.1021%2Fcr950057h). ISSN 0009-2665 (https://www.worldcat.org/issn/0009-2665). PMID 11848850 (https://pubmed.ncbi.nlm.nih.gov/11848850).
42. Anbar AD, Knoll AH (16 August 2002). "Proterozoic Ocean Chemistry and Evolution: A Bioinorganic Bridge?" (https://www.science.org/doi/10.1126/science.1069651). *Science*. **297** (5584): 1137–1142. Bibcode:2002Sci...297.1137A (https://ui.adsabs.harvard.edu/abs/2002Sci...297.1137A). doi:10.1126/science.1069651 (https://doi.org/10.1126%2Fscience.1069651). ISSN 0036-8075 (https://www.worldcat.org/issn/0036-8075). PMID 12183619 (https://pubmed.ncbi.nlm.nih.gov/12183619).
43. Institute MP (6 August 2021). "Nitrogen Inputs in the Ancient Ocean: Underappreciated Bacteria Step Into the Spotlight" (https://scitechdaily.com/nitrogen-inputs-in-the-ancient-ocean-underappreciated-bacteria-step-into-the-spotlight/).
44. Mus F, Crook MB, Garcia K, Garcia Costas A, Geddes BA, Kouri ED, et al. (July 2016). Kelly RM (ed.). "Symbiotic Nitrogen Fixation and the Challenges to Its Extension to Nonlegumes" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4907175). *Applied and Environmental Microbiology*. **82** (13): 3698–3710. Bibcode:2016ApEnM..82.3698M (https://ui.adsabs.harvard.edu/abs/2016ApEnM..82.3698M). doi:10.1128/AEM.01055-16 (https://doi.org/10.1128%2FAEM.01055-16). PMC 4907175 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4907175). PMID 27084023 (https://pubmed.ncbi.nlm.nih.gov/27084023).

45. Dhamad AE, Lessner DJ (October 2020). Atomi H (ed.). "A CRISPRi-dCas9 System for Archaea and Its Use To Examine Gene Function during Nitrogen Fixation by Methanosarcina acetivorans" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7580536). *Applied and Environmental Microbiology*. **86** (21): e01402–20. Bibcode:2020ApEnM..86E1402D (https://ui.adsabs.harvard.edu/abs/2020ApEnM..86E1402D). doi:10.1128/AEM.01402-20 (https://doi.org/10.1128%2FAEM.01402-20). PMC 7580536 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7580536). PMID 32826220 (https://pubmed.ncbi.nlm.nih.gov/32826220).
46. Bae HS, Morrison E, Chanton JP, Ogram A (April 2018). "Methanogens Are Major Contributors to Nitrogen Fixation in Soils of the Florida Everglades" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5861825). *Applied and Environmental Microbiology*. **84** (7): e02222–17. Bibcode:2018ApEnM..84E2222B (https://ui.adsabs.harvard.edu/abs/2018ApEnM..84E2222B). doi:10.1128/AEM.02222-17 (https://doi.org/10.1128%2FAEM.02222-17). PMC 5861825 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5861825). PMID 29374038 (https://pubmed.ncbi.nlm.nih.gov/29374038).
47. Latysheva N, Junker VL, Palmer WJ, Codd GA, Barker D (March 2012). "The evolution of nitrogen fixation in cyanobacteria" (https://doi.org/10.1093%2Fbioinformatics%2Fbts008). *Bioinformatics*. **28** (5): 603–606. doi:10.1093/bioinformatics/bts008 (https://doi.org/10.1093%2Fbioinformatics%2Fbts008). PMID 22238262 (https://pubmed.ncbi.nlm.nih.gov/22238262).
48. Pierella Karlusich JJ, Pelletier E, Lombard F, Carsique M, Dvorak E, Colin S, et al. (July 2021). "Global distribution patterns of marine nitrogen-fixers by imaging and molecular methods" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8260585). *Nature Communications*. **12** (1): 4160. Bibcode:2021NatCo..12.4160P (https://ui.adsabs.harvard.edu/abs/2021NatCo..12.4160P). doi:10.1038/s41467-021-24299-y (https://doi.org/10.1038%2Fs41467-021-24299-y). PMC 8260585 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8260585). PMID 34230473 (https://pubmed.ncbi.nlm.nih.gov/34230473).
49. Ash C (13 August 2021). Ash C, Smith J (eds.). "Some light on diazotrophs". *Science*. **373** (6556): 755.7–756. Bibcode:2021Sci...373..755A (https://ui.adsabs.harvard.edu/abs/2021Sci...373..755A). doi:10.1126/science.373.6556.755-g (https://doi.org/10.1126%2Fscience.373.6556.755-g). ISSN 0036-8075 (https://www.worldcat.org/issn/0036-8075). S2CID 238709371 (https://api.semanticscholar.org/CorpusID:238709371).
50. Kuypers MM, Marchant HK, Kartal B (May 2018). "The microbial nitrogen-cycling network". *Nature Reviews. Microbiology*. **16** (5): 263–276. doi:10.1038/nrmicro.2018.9 (https://doi.org/10.1038%2Fnrmicro.2018.9). hdl:21.11116/0000-0003-B828-1 (https://hdl.handle.net/21.11116%2F0000-0003-B828-1). PMID 29398704 (https://pubmed.ncbi.nlm.nih.gov/29398704). S2CID 3948918 (https://api.semanticscholar.org/CorpusID:39489 18).
51. Bergman B, Sandh G, Lin S, Larsson J, Carpenter EJ (May 2013). "Trichodesmium--a widespread marine cyanobacterium with unusual nitrogen fixation properties" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3655545). *FEMS Microbiology Reviews*. **37** (3): 286–302. doi:10.1111/j.1574-6976.2012.00352.x (https://doi.org/10.1111%2Fj.1574-6976.2012.00352.x). PMC 3655545 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3655545). PMID 22928644 (https://pubmed.ncbi.nlm.nih.gov/22928644).
52. "Large-scale study indicates novel, abundant nitrogen-fixing microbes in surface ocean" (https://www.sciencedaily.com/releases/2018/06/180611133453.htm). *ScienceDaily*. Archived (https://web.archive.org/web/20190608024940/https://www.sciencedaily.com/releases/2018/06/180611133453.htm) from the original on 8 June 2019. Retrieved 8 June 2019.
53. Rolff C, Almesjö L, Elmgren R (5 March 2007). "Nitrogen fixation and abundance of the diazotrophic cyanobacterium Aphanizomenon sp. in the Baltic Proper" (http://www.int-res.com/abstracts/meps/v332/p107-118/). *Marine Ecology Progress Series*. **332**: 107–118. Bibcode:2007MEPS..332..107R (https://ui.adsabs.harvard.edu/abs/2007MEPS..332..107R). doi:10.3354/meps332107 (https://doi.org/10.3354%2Fmeps332107).
54. Carmichael WW (12 October 2001). "Health Effects of Toxin-Producing Cyanobacteria: "The CyanoHABs" ". *Human and Ecological Risk Assessment*. **7** (5): 1393–1407. Bibcode:2001HERA....7.1393C (https://ui.adsabs.harvard.edu/abs/2001HERA....7.1393C). doi:10.1080/20018091095087 (https://doi.org/10.1080%2F20018091095087). ISSN 1080-7039 (https://www.worldcat.org/issn/1080-7039). S2CID 83939897 (https://api.semanticscholar.org/CorpusID:83939897).

55. Bothe H, Schmitz O, Yates MG, Newton WE (December 2010). "Nitrogen fixation and hydrogen metabolism in cyanobacteria" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3008169). *Microbiology and Molecular Biology Reviews*. **74** (4): 529–551. doi:10.1128/MMBR.00033-10 (https://doi.org/10.1128%2FMMBR.00033-10). PMC 3008169 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3008169). PMID 21119016 (https://pubmed.ncbi.nlm.nih.gov/21119016).
56. Wong C (11 April 2024). "Scientists discover first algae that can fix nitrogen — thanks to a tiny cell structure" (https://www.nature.com/articles/d41586-024-01046-z). *Nature*. doi:10.1038/d41586-024-01046-z (https://doi.org/10.1038%2Fd41586-024-01046-z). PMID 38605201 (https://pubmed.ncbi.nlm.nih.gov/38605201).
57. Kuypers MM, Marchant HK, Kartal B (May 2018). "The microbial nitrogen-cycling network". *Nature Reviews. Microbiology*. **16** (5): 263–276. doi:10.1038/nrmicro.2018.9 (https://doi.org/10.1038%2Fnrmicro.2018.9). hdl:21.11116/0000-0003-B828-1 (https://hdl.handle.net/21.11116%2F0000-0003-B828-1). PMID 29398704 (https://pubmed.ncbi.nlm.nih.gov/29398704). S2CID 3948918 (https://api.semanticscholar.org/CorpusID:3948918).
58. Smil V (2000). *Cycles of Life*. Scientific American Library.
59. "Nitrogen Fixation and Inoculation of Forage Legumes" (https://web.archive.org/web/20161202170130/http://www1.foragebeef.ca/$Foragebeef/frgebeef.nsf/all/frg90/$FILE/fertilitylegumefixation.pdf) (PDF). Archived from the original (http://www1.foragebeef.ca/$Foragebeef/frgebeef.nsf/all/frg90/$FILE/fertilitylegumefixation.pdf) (PDF) on 2 December 2016.
60. Dawson JO (2008). "Ecology of Actinorhizal Plants". *Nitrogen-fixing Actinorhizal Symbioses*. Nitrogen Fixation: Origins, Applications, and Research Progress. Vol. 6. Springer. pp. 199–234. doi:10.1007/978-1-4020-3547-0_8 (https://doi.org/10.1007%2F978-1-4020-3547-0_8). ISBN 978-1-4020-3540-1.
61. Op den Camp R, Streng A, De Mita S, Cao Q, Polone E, Liu W, et al. (February 2011). "LysM-type mycorrhizal receptor recruited for rhizobium symbiosis in nonlegume Parasponia". *Science*. **331** (6019): 909–12. Bibcode:2011Sci...331..909O (https://ui.adsabs.harvard.edu/abs/2011Sci...331..909O). doi:10.1126/science.1198181 (https://doi.org/10.1126%2Fscience.1198181). PMID 21205637 (https://pubmed.ncbi.nlm.nih.gov/21205637). S2CID 20501765 (https://api.semanticscholar.org/CorpusID:20501765).
62. "Cycad biology, Article 1: Corraloid roots of cycads" (http://www1.biologie.uni-hamburg.de/b-online/library/cycads/corraloid.htm). *www1.biologie.uni-hamburg.de*. Retrieved 14 October 2021.
63. Rai AN (2000). "Cyanobacterium-plant symbioses" (https://doi.org/10.1046%2Fj.1469-8137.2000.00720.x). *New Phytologist*. **147** (3): 449–481. doi:10.1046/j.1469-8137.2000.00720.x (https://doi.org/10.1046%2Fj.1469-8137.2000.00720.x). PMID 33862930 (https://pubmed.ncbi.nlm.nih.gov/33862930).
64. Van Deynze A, Zamora P, Delaux PM, Heitmann C, Jayaraman D, Rajasekar S, et al. (August 2018). "Nitrogen fixation in a landrace of maize is supported by a mucilage-associated diazotrophic microbiota" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6080747). *PLOS Biology*. **16** (8): e2006352. doi:10.1371/journal.pbio.2006352 (https://doi.org/10.1371%2Fjournal.pbio.2006352). PMC 6080747 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6080747). PMID 30086128 (https://pubmed.ncbi.nlm.nih.gov/30086128).
65. Pskowski M (16 July 2019). "Indigenous Maize: Who Owns the Rights to Mexico's 'Wonder' Plant?" (https://e360.yale.edu/features/indigenous-maize-who-owns-the-rights-to-mexicos-wonder-plant). *Yale E360*.
66. Eyde S (1909). "The Manufacture of Nitrates from the Atmosphere by the Electric Arc—Birkeland-Eyde Process". *Journal of the Royal Society of Arts*. **57** (2949): 568–576. JSTOR 41338647 (https://www.jstor.org/stable/41338647).
67. Heinrich H, Nevbner R (1934). "Die Umwandlungsgleichung $Ba(CN)_2 \rightarrow BaCN_2 + C$ im Temperaturgebiet von 500 bis 1000 °C" (http://onlinelibrary.wiley.com/doi/10.1002/bbpc.19340401005/abstract) [The conversion reaction $Ba(CN)_2 \rightarrow BaCN_2 + C$ in the temperature range from 500 to 1,000 °C]. *Z. Elektrochem. Angew. Phys. Chem*. **40** (10): 693–698. doi:10.1002/bbpc.19340401005 (https://doi.org/10.1002%2Fbbpc.19340401005). S2CID 179115181 (https://api.semanticscholar.org/CorpusID:179115181). Archived (https://web.archive.org/web/20160820203326/http://onlinelibrary.wiley.com/doi/10.1002/bbpc.19340401005/abstract) from the original on 20 August 2016. Retrieved 8 August 2016.
68. Curtis HA (1932). *Fixed nitrogen* (https://books.google.com/books?id=87XQAAAAMAAJ).
69. Smil, V. 2004. Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production, MIT Press.

70. Glibert PM, Maranger R, Sobota DJ, Bouwman L (1 October 2014). "The Haber Bosch–harmful algal bloom (HB–HAB) link" (https://doi.org/10.1088%2F1748-9326%2F9%2F10%2F105001). *Environmental Research Letters*. **9** (10): 105001. Bibcode:2014ERL.....9j5001G (https://ui.adsabs.harvard.edu/abs/2014ERL.....9j5001G). doi:10.1088/1748-9326/9/10/105001 (https://doi.org/10.1088%2F1748-9326%2F9%2F10%2F105001). ISSN 1748-9326 (https://www.worldcat.org/issn/1748-9326). S2CID 154724892 (https://api.semanticscholar.org/CorpusID:154724892).
71. Erisman JW, Sutton MA, Galloway J, Klimont Z, Winiwarter W (October 2008). "How a century of ammonia synthesis changed the world". *Nature Geoscience*. **1** (10): 636–639. Bibcode:2008NatGe...1..636E (https://ui.adsabs.harvard.edu/abs/2008NatGe...1..636E). doi:10.1038/ngeo325 (https://doi.org/10.1038%2Fngeo325). ISSN 1752-0908 (https://www.worldcat.org/issn/1752-0908). S2CID 94880859 (https://api.semanticscholar.org/CorpusID:94880859).
72. Allen AD, Senoff CV (1965). "Nitrogenopentammineruthenium(II) complexes". *J. Chem. Soc., Chem. Commun.* (24): 621–622. doi:10.1039/C19650000621 (https://doi.org/10.1039%2FC19650000621).
73. Chalkley MJ, Drover MW, Peters JC (June 2020). "Catalytic N_2-to-NH_3 (or -N_2H_4) Conversion by Well-Defined Molecular Coordination Complexes" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7493999). *Chemical Reviews*. **120** (12): 5582–5636. doi:10.1021/acs.chemrev.9b00638 (https://doi.org/10.1021%2Facs.chemrev.9b00638). PMC 7493999 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7493999). PMID 32352271 (https://pubmed.ncbi.nlm.nih.gov/32352271).
74. Tuck AF (October 1976). "Production of nitrogen oxides by lightning discharges". *Quarterly Journal of the Royal Meteorological Society*. **102** (434): 749–755. Bibcode:1976QJRMS.102..749T (https://ui.adsabs.harvard.edu/abs/1976QJRMS.102..749T). doi:10.1002/qj.49710243404 (https://doi.org/10.1002%2Fqj.49710243404). ISSN 0035-9009 (https://www.worldcat.org/issn/0035-9009).
75. Hill RD (August 1979). "Atmospheric Nitrogen Fixation by Lightning" (https://doi.org/10.1175%2F1520-0469%281980%29037%3C0179%3AANFBL%3E2.0.CO%3B2). *Journal of the Atmospheric Sciences*. **37**: 179–192. Bibcode:1980JAtS...37..179H (https://ui.adsabs.harvard.edu/abs/1980JAtS...37..179H). doi:10.1175/1520-0469(1980)037<0179:ANFBL>2.0.CO;2 (https://doi.org/10.1175%2F1520-0469%281980%29037%3C0179%3AANFBL%3E2.0.CO%3B2). ISSN 1520-0469 (https://www.worldcat.org/issn/1520-0469).
76. Levin JS (1984). "Tropospheric Sources of NOx: Lightning And Biology" (https://journals.ohiolink.edu/pg_99?126555292207822::NO::P99_ENTITY_ID,P99_ENTITY_TYPE:20567211,MAIN_FILE&cs=38gV8XNFDWVznjRjSa1erAIidpqPJBYgnOix4OM5wvpjv8vJAbG2NGhNYwWAVItkNehLIgXVYuozMCrUrENyuYA). Retrieved 29 November 2018.

External links

- Hirsch AM (2009). "A Brief History of the Discovery of Nitrogen-fixing Organisms" (http://www.mcdb.ucla.edu/Research/Hirsch/imagesb/HistoryDiscoveryN2fixingOrganisms.pdf) (PDF). University of California, Los Angeles.
- "Marine Nitrogen Fixation laboratory" (http://dornsife.usc.edu/labs/capone). University of Southern California.
- "Travis P. Hignett Collection of Fixed Nitrogen Research Laboratory Photographs // Science History Institute Digital Collections" (https://digital.sciencehistory.org/collections/gm80hv42t). *digital.sciencehistory.org*. Retrieved 16 August 2019. Science History Institute Digital Collections (Photographs depicting numerous stages of the nitrogen fixation process and the various equipment and apparatus used in the production of atmospheric nitrogen, including generators, compressors, filters, thermostats, and vacuum and blast furnaces).
- "Proposed Process for the Fixation of Atmospheric Nitrogen (https://books.google.com/books?id=p4o9AQAAIAAJ)", historical perspective, Scientific American, 13 July 1878, p. 21
- A global ocean snapshot of nitrogen fixers by matching sequences to cells in the Tara Ocean (https://naturemicrobiologycommunity.nature.com/posts/a-global-ocean-snapshot-of-nitrogen-fixers-by-matching-sequences-to-cells-in-the-tara-ocean)