



FHSST Authors

**The Free High School Science Texts:
Textbooks for High School Students
Studying the Sciences
Chemistry
Grades 10 - 12**

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this a continuously evolving resource!

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Chapter 19

Global Cycles: The Nitrogen Cycle - Grade 10

19.1 Introduction

The earth's atmosphere is made up of about 78% nitrogen, making it the largest pool of this gas. Nitrogen is essential for many biological processes. It is in all amino acids, proteins and nucleic acids. As you will see in a later chapter, these compounds are needed to build tissues, transport substances around the body, and control what happens in living organisms. In plants, much of the nitrogen is used in chlorophyll molecules which are needed for photosynthesis and growth.

So, if nitrogen is so essential for life, how does it go from being a gas in the atmosphere to being part of living organisms such as plants and animals? The problem with nitrogen is that it is an 'inert' gas, which means that it is unavailable to living organisms in its gaseous form. This is because of the strong triple bond between its atoms that makes it difficult to break. Something needs to happen to the nitrogen gas to change it into a form that it can be used. And at some later stage, these new compounds must be converted back into nitrogen gas so that the amount of nitrogen in the atmosphere stays the same. This process of changing nitrogen into different forms is called the **nitrogen cycle** (figure 19.1).



Definition: The nitrogen cycle

The nitrogen cycle is a biogeochemical cycle that describes how nitrogen and nitrogen-containing compounds are changed in nature.

Very broadly, the nitrogen cycle is made up of the following processes:

- **Nitrogen fixation** - The process of converting inert nitrogen gas into more useable nitrogen compounds such as ammonia.
- **Nitrification** - The conversion of ammonia into nitrites and then into nitrates, which can be absorbed and used by plants.
- **Denitrification** - The conversion of nitrates back into nitrogen gas in the atmosphere.

We are going to look at each of these processes in more detail.

19.2 Nitrogen fixation

Nitrogen fixation is needed to change gaseous nitrogen into forms such as ammonia that are more useful to living organisms. Some fixation occurs in lightning strikes and in industrial processes,

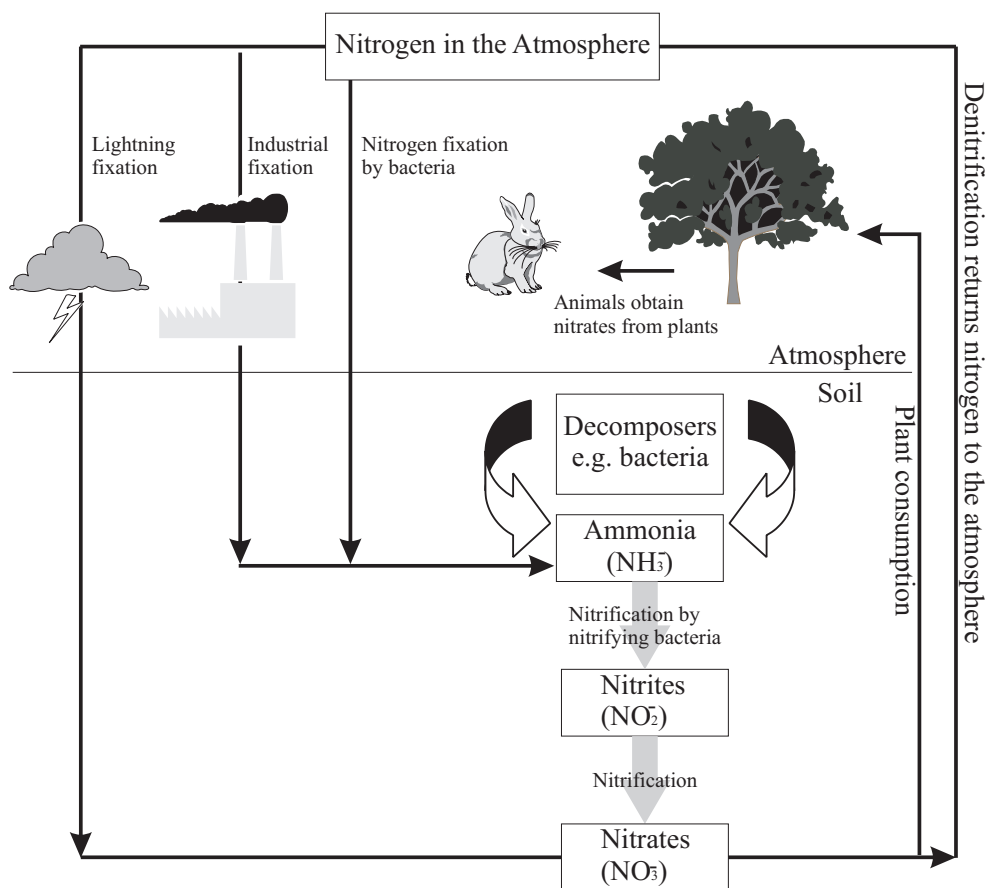


Figure 19.1: A simplified diagram of the nitrogen cycle

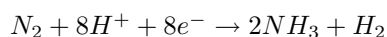
but most fixation is done by different types of bacteria living either in the soil or in parts of the plants.

1. Biological fixation

Some bacteria are able to fix nitrogen. They use an enzyme called *nitrogenase* to combine gaseous nitrogen with hydrogen to form ammonia. The bacteria then use some of this ammonia to produce their own organic compounds, while what is left of the ammonia becomes available in the soil.

Some of these bacteria are free-living, in other words they live in the soil. Others live in the root nodules of legumes (e.g. soy, peas and beans). Here they form a mutualistic relationship with the plant. The bacteria get carbohydrates (food) from the plant and, in exchange, produce ammonia which can be converted into nitrogen compounds that are essential for the survival of the plant. In nutrient-poor soils, planting lots of legumes can help to enrich the soil with nitrogen compounds.

A simplified equation for biological nitrogen fixation is:



Energy is used in the process, but this is not shown in the above equation.

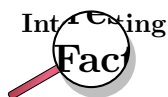
Another important source of ammonia in the soil is **decomposition**. When animals and plants die, the nitrogen compounds that were present in them are broken down and converted into ammonia. This process is carried out by decomposition bacteria and fungi in the soil.

2. Industrial nitrogen fixation

In the Haber-Bosch process, nitrogen (N_2) is converted together with hydrogen gas (H_2) into ammonia (NH_3) fertiliser. This is an artificial process.

3. Lightning

In the atmosphere, lightning and photons are important in the reaction between nitrogen (N_2) and oxygen (O_2) to form nitric oxide (NO) and then nitrates.



It is interesting to note that by cultivating legumes, using the Haber-Bosch process to manufacture chemical fertilisers and increasing pollution from vehicles and industry, humans have more than doubled the amount of nitrogen that would normally be changed from nitrogen gas into a biologically useful form. This has serious environmental consequences.

19.3 Nitrification

Nitrification involves two biological oxidation reactions: firstly, the oxidation of ammonia with oxygen to form nitrite (NO_2^-) and secondly the oxidation of these nitrites into nitrates.

1. $NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^-$ (production of *nitrites*)
2. $NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^-$ (production of *nitrates*)

Nitrification is an important step in the nitrogen cycle in soil because it converts the ammonia (from the nitrogen fixing part of the cycle) into nitrates, which are easily absorbed by the roots of plants. This absorption of nitrates by plants is called **assimilation**. Once the nitrates have been assimilated by the plants, they become part of the plants' proteins. These plant proteins are then available to be eaten by animals. In other words, animals (including humans) obtain their own nitrogen by feeding on plants. Nitrification is performed by bacteria in the soil, called *nitrifying bacteria*.

Activity :: Case Study : Nitrates in drinking water

Read the information below and then carry out your own research to help you answer the questions that follow.

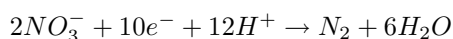
The negatively charged nitrate ion is not held onto soil particles and so can be easily washed out of the soil. This is called **leaching**. In this way, valuable nitrogen can be lost from the soil, reducing the soil's fertility. The nitrates can then accumulate in groundwater, and eventually in drinking water. There are strict regulations that control how much nitrate can be present in drinking water, because nitrates can be reduced to highly reactive nitrites by microorganisms in the gut. Nitrites are absorbed from the gut and bind to haemoglobin (the pigment in blood that helps to transport oxygen around the body). This reduces the ability of the haemoglobin to carry oxygen. In young babies this can lead to respiratory distress, a condition known as "blue baby syndrome".

1. How is nitrate concentration in water measured?
2. What concentration of nitrates in drinking water is considered acceptable? You can use drinking water standards for any part of the world, if you can't find any for South Africa.
3. What is 'blue baby syndrome' and what are the symptoms of the disease?

19.4 Denitrification

Denitrification is the process of reducing nitrate and nitrite into gaseous nitrogen. The process is carried out by *denitrification bacteria*. The nitrogen that is produced is returned to the atmosphere to complete the nitrogen cycle.

The equation for the reaction is:



19.5 Human Influences on the Nitrogen Cycle

Humans have contributed significantly to the nitrogen cycle in a number of ways.

- Both **artificial fertilisation** and the planting of **nitrogen fixing crops**, increase the amount of nitrogen in the soil. In some ways this has positive effects because it increases the fertility of the soil, and means that agricultural productivity is high. On the other hand, however, if there is too much nitrogen in the soil, it can run off into nearby water courses such as rivers, or can become part of the groundwater supply as we mentioned earlier. Increased nitrogen in rivers and dams can lead to a problem called **eutrophication**. Eutrophication is a process where water bodies such as rivers, estuaries, dams and slow-moving streams receive excess nutrients (e.g. nitrogen and phosphorus compounds) that stimulate excessive plant growth. Sometimes this can cause certain plant species to be favoured over the others and one species may 'take over' the ecosystem, resulting in a decrease in plant diversity. This is called a 'bloom'. Eutrophication also affects water quality. When the plants die and decompose, large amounts of oxygen are used up and this can cause other animals in the water to die.

Activity :: Case Study : Fertiliser use in South Africa

Refer to the data table below, which shows the average fertiliser use (in kilograms per hectare or kg/ha) over a number of years for South Africa and the world. Then answer the questions that follow:

	1965	1970	1975	1980	1985	1990	1995	2000	2002
SA	27.9	42.2	57.7	80.3	66.6	54.9	48.5	47.1	61.4
World	34.0	48.9	63.9	80.6	86.7	90.9	84.9	88.2	91.9

1. On the same set of axes, draw two line graphs to show how fertiliser use has changed in SA and the world between 1965 and 2002.
2. Describe the trend you see for...
 - (a) the world
 - (b) South Africa
3. Suggest a reason why the world's fertiliser use has changed in this way over time.
4. Do you see the same pattern for South Africa?
5. Try to suggest a reason for the differences you see in the fertiliser use data for South Africa.
6. One of the problems with increased fertiliser use is that there is a greater chance of nutrient runoff into rivers and dams, and therefore a greater danger of eutrophication. In groups of 5-6, discuss the following questions:
 - (a) What could farmers do to try to reduce the risk of nutrient runoff from fields into water systems? Try to think of at least 3 different strategies that they could use.

- (b) Imagine you are going to give a presentation on eutrophication to a group of farmers who know nothing about it. How will you educate them about the dangers? How will you convince them that it is in their interests to change their farming practices? Present your ideas to the class.

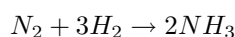
- **Atmospheric pollution** is another problem. The main culprits are nitrous oxide (N_2O), nitric oxide (NO) and nitrogen dioxide (NO_2). Most of these gases result either from emissions from agricultural soils (and particularly artificial fertilisers), or from the combustion of fossil fuels in industry or motor vehicles. The combustion (burning) of nitrogen-bearing fuels such as coal and oil releases this nitrogen as N_2 or NO gases. Both NO_2 and NO can combine with water droplets in the atmosphere to form **acid rain**. Furthermore, both NO and NO_2 contribute to the depletion of the ozone layer and some are **greenhouse gases**. In high concentrations these gases can contribute towards **global warming**.

19.6 The industrial fixation of nitrogen

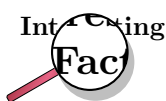
A number of industrial processes are able to fix nitrogen into different compounds and then convert these compounds into fertilisers. In the descriptions below, you will see how atmospheric nitrogen is fixed to produce ammonia, how ammonia is then reacted with oxygen to form nitric acid and how nitric acid and ammonia are then used to produce the fertiliser, ammonium nitrate.

- **Preparation of ammonia (NH_3)**

The industrial preparation of ammonia is known as the **Haber-Bosch process**. At a high pressure and a temperature of approximately $500^\circ C$, and in the presence of a suitable catalyst (usually iron), nitrogen and hydrogen react according to the following equation:



Ammonia is used in the preparation of artificial fertilisers such as $(NH_4)_2SO_4$ and is also used in cleaning agents and cooling installations.



Fritz Haber and Carl Bosch were the two men responsible for developing the Haber-Bosch process. In 1918, Haber was awarded the Nobel Prize in Chemistry for his work. The Haber-Bosch process was a milestone in industrial chemistry because it meant that nitrogenous fertilisers were cheaper and much more easily available. At the time, this was very important in providing food for the growing human population.

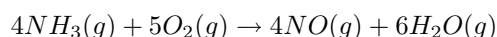
Haber also played a major role in the development of chemical warfare in World War I. Part of this work included the development of gas masks with absorbent filters. He also led the teams that developed chlorine gas and other deadly gases for use in trench warfare. His wife, Clara Immerwahr, also a chemist, opposed his work on poison gas and committed suicide with his service weapon in their garden. During the 1920s, scientists working at his institute also developed the cyanide gas formulation Zyklon B, which was used as an insecticide and also later, after he left the programme, in the Nazi extermination camps.

Haber was Jewish by birth, but converted from Judaism in order to be more accepted in Germany. Despite this, he was forced to leave the country in 1933 because he was Jewish 'by definition' (his mother was Jewish). He died in 1934 at the age of 65. Many members of his extended family died in the Nazi concentration camps, possibly gassed by Zyklon B.

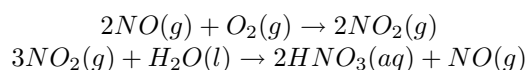
- **Preparation of nitric acid (HNO₃)**

Nitric acid is used to prepare fertilisers and explosives. The industrial preparation of nitric acid is known as the **Ostwald process**. The Ostwald process involves the conversion of ammonia into nitric acid in various stages:

Firstly, ammonia is heated with oxygen in the presence of a platinum catalyst to form nitric oxide and water.



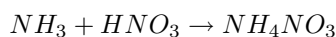
Secondly, nitric oxide reacts with oxygen to form nitrogen dioxide. This gas is then readily absorbed by the water to produce nitric acid. A portion of nitrogen dioxide is reduced back to nitric oxide.



The NO is recycled, and the acid is concentrated to the required strength by a process called *distillation*.

- **Preparation of ammonium nitrate**

Ammonium nitrate is used as a fertiliser, as an explosive and also in the preparation of 'laughing gas' which is used as an anaesthetic. Ammonium nitrate is prepared by reacting ammonia with nitric acid:



Activity :: Debate : Fertiliser use

Divide the class into two groups to debate the following topic:

Increasing the use of artificial fertilisers is the best solution to meet the growing food needs of the world's human population.

One group should take the position of *agreeing* with the statement, and the other should *disagree*. In your groups, discuss reasons why you have the opinion that you do, and record some notes of your discussion. Your teacher will then explain to you how to proceed with the debate.

19.7 Summary

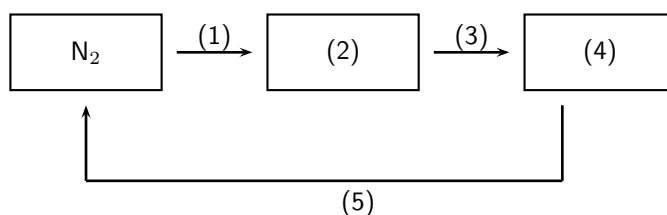
- **Nitrogen** is essential for life on earth, since it forms part of **amino acids**, **proteins** and **nucleic acids**.
- The **atmosphere** is composed mostly of nitrogen gas, but the gas is **inert**, meaning that it is not available to living organisms in its gaseous form.
- The **nitrogen cycle** describes how nitrogen and nitrogen-containing compounds are changed into different forms in nature.

- The nitrogen cycle consists of three major processes: **nitrogen fixation**, **nitrification** and **denitrification**.
- **Nitrogen fixation** is the conversion of atmospheric nitrogen into compounds such as ammonia, that are more easily used.
- Nitrogen can be fixed **biologically** through the actions of **bacteria**, **industrially** through the **Haber-Bosch process** or by **lightning**.
- **Nitrification** converts ammonia into **nitrites** and **nitrates**, which can be easily **assimilated** by plants.
- **Denitrification** converts nitrites and nitrates back into gaseous nitrogen to complete the nitrogen cycle.
- **Humans** have had a number of **impacts** on the nitrogen cycle. The production of **artificial fertilisers** for example, means that there is a greater chance of runoff into water systems. In some cases, **eutrophication** may occur.
- **Eutrophication** is the enrichment of water systems with excess nutrients, which may stimulate excessive plant growth at the expense of other parts of the ecosystem.
- Many nitrogen gases such as NO, N₂O and NO₂ are released by agricultural soils and artificial fertilisers. These gases may combine with water vapour in the atmosphere and result in **acid rain**. Some of these gases are also greenhouse gases and may contribute towards **global warming**.
- A number of **industrial processes** are used to produce **artificial fertilisers**.
- The **Haber-Bosch process** converts atmospheric nitrogen into **ammonia**.
- The **Ostwald process** reacts ammonia with oxygen to produce **nitric acid**, which is used in the preparation of fertilisers and explosives.
- If ammonia and nitric acid react, the product is **ammonium nitrate**, which is used as a fertiliser and as an explosive.



Exercise: Summary Exercise

1. Look at the diagram and the descriptions of the nitrogen cycle earlier in the chapter:
 - (a) Would you describe the changes that take place in the nitrogen cycle as *chemical* or *physical* changes? Explain your answer.
 - (b) Are the changes that take place in the water cycle *physical* or *chemical* changes? Explain your answer.
2. Explain what is meant by each of the following terms:
 - (a) nitrogen fixing
 - (b) fertiliser
 - (c) eutrophication
3. Explain why the fixing of atmospheric nitrogen is so important for the survival of life on earth.
4. Refer to the diagram below and then answer the questions that follow:



- (a) Explain the role of *decomposers* in the nitrogen cycle.
 - (b) If the process taking place at (3) is *nitrification*, then label the processes at (1) and (5).
 - (c) Identify the nitrogen products at (2) and (4).
 - (d) On the diagram, indicate the type of *bacteria* that are involved in each stage of the nitrogen cycle.
 - (e) In industry, what process is used to produce the compound at 2?
 - (f) Does the diagram above show a 'cycle'? Explain your answer.
5. NO and NO₂ are both nitrogen compounds:
 - (a) Explain how each of these compounds is formed?
 - (b) What effect does each of these compounds have in the environment?
 6. There are a number of arguments both 'for' and 'against' the use of artificial fertilisers. Draw a table to summarise the advantages and disadvantages of their use.

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