Cross Current International Journal of Agriculture and Veterinary Sciences
Abbreviated Key Title: Cross Current Int J Agri Vet Sci
ISSN: 2663-2454 (Print) & Open Access
DOI: 10.36344/ccijavs.2023.v05i04.002

Volume-5 | Issue-4 | Jul-Aug, 2023 |

Review Article

Key to Life, Risks and Cycle of Nitrogen

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| **Received:** 17.06.2023 | **Accepted:** 22.07.2023 | **Published:** 25.07.2023 |

Abstract: Nitrogen is practically inert and largely unreactive, existing mostly in molecular form (N_2) in the atmosphere and unsuitable for uptake by living matter. But it is one of the most commonly used practices to increase crop yields throughout the world because of the abundant availability of N fertilizers and their great effectiveness to increase yields compared with other organic fertilizers, such as manure and compost. It is essential to achieve production levels, which enable global food security, without compromising environmental security. Excessive application of N fertilizers in the last several decades, however, has resulted in undesirable consequences of soil and environmental degradations, such as soil acidification, N leaching to the groundwater, and greenhouse gas (N_2O) emissions. Crop yields have declined in places where soil acidification is high due to the unavailability of major nutrients and basic cations and the toxic effect of acidic cations. Other disadvantages of excessive N fertilization include increased cost of fertilization, reduced N-use efficiency, and negative impact on human and livestock health. Diffuse pollution, caused by N fertilization in agriculture, has become a global problem that is difficult to solve. Nearly half of N fertilizer input is not used by crops and is lost into the environment via the emission of gases or by polluting water bodies. The N pollution level expected by 2050 is projected to be 150% higher than in 2010, with the agricultural sector accounting for 60% of this increase. So, to reduce these problems globally, understanding of nitrogen cycle and nutrient use efficiency is important.
Keywords: Nitrogen; efficiency; importance; risk.

INTRODUCTION

Nitrogen (N), carbon, hydrogen, oxygen, and phosphorus are the elements on which life is based (Fowler *et al.*, 2013). Among them, N is the fundamental element in the formation of amino acids, which, in turn, are the basic components of proteins. Nitrogen is in the soil under our feet, in the water we drink, and in the air we breathe. This element makes up 78% of the air in the atmosphere where it is practically inert and largely unreactive, existing mostly in molecular form (N_2). Nitrogen gas in the atmosphere is unsuitable for uptake by living matter. Human protein intake depends on the capacity of plants to take N into the food chain, and it requires certain transformations to be used by plants and later by animals for this to happen. Robertson and Groffman (2007) defined the N cycle and its different forms. Atmospheric dinitrogen gas is turned into ammonia (NH_3) and fixed in the soil through the fixation process. Nitrogen is important to all living things, including us. It plays a key role in plant growth: too little nitrogen and plants cannot thrive, leading to low crop yields; but too much nitrogen can be toxic to plants (Britto and Kronzuker, 2002). Nitrogen is necessary for our food supply, but excess nitrogen can harm the environment and our health. Therefore, this review aimed to know the importance, risk, and cycle of nitrogen to the atmosphere-soil-plant relationship.

Importance of Nitrogen

Nitrogen is extremely important to living material. Plants, animals, and humans could not live without it. Nitrogen is essential for all living things because it is a major part of amino acids, which are the building blocks of proteins, and of nucleic acids such as DNA, which transfers genetic information to subsequent generations of organisms. Nitrogen is essential for plants to grow and survive. Without proteins – some as structural units, others as enzymes – plants die. Nitrogen makes up a large part of chlorophyll, which plants need for photosynthesis, the process of using the sun's energy to make sugars from water and carbon dioxide. Nitrogen forms part of energy-transfer compounds such as ATP (adenosine triphosphate), which lets cells conserve and use energy

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Citation: Desta Abayechaw & Wondimkun Dikr (2023). Key to Life, Risks and Cycle of Nitrogen. *Cross Current Int J Agri Vet Sci*, *5*(4), 43-48.

released via metabolism. Plants also need nucleic acids such as DNA to grow and reproduce. Plants get nitrogen in a different way than animals, taking it from water and soil in the form of nitrates and ammonium. Plants lacking in nitrogen turn yellow and stop growing, and they bear smaller-than-average fruits and flowers.

When other resources such as light and water are abundant, ecosystem productivity and biomass are often limited by the amount of available nitrogen. This is the primary reason why nitrogen is an essential part of fertilizers used to enhance soil quality for agricultural activities. The application of nitrogen increases the greenness of plants, CO2 assimilation rate, and crop quality yield and improves resistance to environmental stresses such as limited water availability and saline soil conditions (Bondada *et al.*, 1996; Chen *et al.*, 2010). Hou *et al.*, (2007) found that nitrogen application is more important than the other major essential fertilizers/nutrients for successful crop production. Consequently, the N requirement is the most central feature of plant production (Bondada and Oosterhuis, 2001). Slow development of plants and early leaf senescence due to deficient N can cause decreased both crop production and quality (Dong *et al.*, 2012). Excessive N fertilizer application is a common practice by farmers of cotton regions in the northwest (Mao, 2013) which is not cost-effective for crop production, and excess N prolongs the vegetative growth period, delays maturity (Hodges, 2002), decreases sugar content, and also attracts insect pest and causes disease epidemics.

Figure 1: Application of nitrogen fertilizer to crop

Risk of Nitrogen

Societies around the world are placing increasing emphasis on managing and enhancing water, soil, and air quality in order to achieve widely shared sustainability goals (Folke *et al.*, 2021). Maintaining water quality in marine ecosystems has become a critical focus of environmental management (Pashaei *et al.*, 2015), and the importance of soil quality is rapidly emerging as a key indicator of sustainable land management practices (Sofo *et al.*, 2021). Nitrogen pollution is caused when some nitrogen compounds – like ammonia and nitrous oxide – become too abundant. This pollution is sometimes the result of synthetic fertilizer use. Or, another cause is the breakdown of high volumes of animal manures and slurry – often found in intensive livestock units.

Nitrogen fertilizers used in agriculture increased from 10 Tg N ha^{-1} (1961) to 77 Tg N ha^{-1} (2016) (Elrys *et al.*, 2020; FAO, 2020). Nearly half of the N fertilizer supplied is not used by crops and is lost to the ecosystem through volatilization, run-off, or leaching (Billen, and Garnier, 2013). These losses lead to environmental problems, such as the release of greenhouse gases, pollution of water bodies, soil acidification, or biodiversity reduction. The atmospheric level of N pollution is expected by, 2050, to be in the range of 102–156% higher than in 2010 with the agricultural sector accounting for 60% of this increase (FAO, 2020). Developing countries, where 76% of the world population lives, use more N than developed countries. Asia is the greatest consumer of N fertilizer and energy in the world and is consequently responsible for a considerable proportion of the global creation of N_2O. Approximately 58% of N is currently emitted into the environment as a pollutant (FAO, 2020).

Nitrogen Cycle

The nitrogen cycle is a repeating cycle of processes during which nitrogen moves through both living and non-living things: the atmosphere, soil, water, plants, animals, and bacteria. In order to move through the different parts of the cycle, nitrogen must change forms. In the atmosphere, nitrogen exists as a gas (N_2), but in the soils, it exists as nitrogen oxide

(NO), and nitrogen dioxide (NO_2), and when used as a fertilizer, can be found in other forms, such as ammonia (NH_3), which can be processed even further into a different fertilizer, ammonium nitrate, or NH_4NO_3.

There are five stages in the nitrogen cycle, and we will now discuss each of them in turn: fixation or volatilization, mineralization, nitrification, immobilization, and denitrification. In this image, microbes in the soil turn nitrogen gas (N_2) into what is called volatile ammonia (NH_3), so the fixation process is called volatilization. Leaching is where certain forms of nitrogen (such as nitrate, or (NO_3) become dissolved in water and leak out of the soil, potentially polluting waterways.

Stage 1: Nitrogen fixation

In this stage, nitrogen moves from the atmosphere into the soil. Earth's atmosphere contains a huge pool of nitrogen gas (N_2). But this nitrogen is "unavailable" to plants because the gaseous form cannot be used directly by plants without transforming. To be used by plants, the N_2 must be transformed through a process called nitrogen fixation. Fixation converts nitrogen in the atmosphere into forms that plants can absorb through their root systems. A small amount of nitrogen can be fixed when lightning provides the energy needed for N_2 to react with oxygen, producing nitrogen oxide (NO), and nitrogen dioxide (NO_2. These forms of nitrogen then enter soils through rain or snow. Nitrogen can also be fixed through the industrial process that creates fertilizer. This form of fixing occurs under high heat and pressure, during which atmospheric nitrogen and hydrogen are combined to form ammonia (NH_3), which may then be processed further, to produce ammonium nitrate (NH_4NO_3), a form of nitrogen that can be added to soils and used by plants.

Most nitrogen fixation occurs naturally, in the soil, by bacteria. Biological N fixation (BNF) is a microbial process that converts molecular N_2 gas to reactive, biologically available nitrogen forms (Marino & Howarth, 2009). Nitrogen fixation occurs when atmospheric nitrogen is converted to ammonia by nitrogenase, a pair of bacterial enzymes found in a few bacteria species, including cyanobacteria. However, most BNF is undertaken by Rhizobium bacteria which form a symbiotic relationship with leguminous plants (Herridge *et al.,* 2008). Legumes not only are widely cultivated crop plants but also exist extensively in all ecosystems. The nitrogen fixed by biological fixation is first used to create ammonium ($NH4^+$) ions which are subsequently incorporated into amino acids (Abu, 2018). In the Figure below, you can see nitrogen fixation and exchange of form occurring in the soil. Some bacteria attach to plant roots and have a symbiotic (beneficial for both the plant and the bacteria) relationship with the plant (Peoples *et al.,* 1995). The bacteria get energy through photosynthesis and, in return, they fix nitrogen into a form the plant needs. The fixed nitrogen is then carried to other parts of the plant and is used to form plant tissues, so the plant can grow. Other bacteria live freely in soils or water and can fix nitrogen without this symbiotic relationship. These bacteria can also create forms of nitrogen that can be used by organisms.

Stage 2: Mineralization

This stage takes place in the soil. Nitrogen moves from organic materials, such as manure or plant materials to an inorganic form of nitrogen that plants can use. Eventually, the plant's nutrients are used up and the plant dies and decomposes. This becomes important in the second stage of the nitrogen cycle. Mineralization happens when microbes act on organic material, such as animal manure or decomposing plant or animal material, and begin to convert it to a form of nitrogen that can be used by plants. All plants under cultivation, except legumes (plants with seed pods that split in half, such as lentils, beans, peas, or peanuts) get the nitrogen they require through the soil. Legumes get nitrogen through fixation that occurs in their root nodules, as described above. The first form of nitrogen produced by the process of mineralization is ammonia (NH_3). The NH_3 in the soil then reacts with water to form ammonium (NH_4). This ammonium is held in the soils and is available for use by plants that do not get nitrogen through the symbiotic nitrogen-fixing relationship described above.

Stage 3: Nitrification

The third stage, nitrification, also occurs in soils. During nitrification, the ammonia in the soils, produced during mineralization, is converted into compounds called nitrites (NO_2^-), and nitrates (NO_3^-). Nitrates can be used by plants and animals that consume the plants. Some bacteria in the soil can turn ammonia into nitrites. Although nitrite is not usable by plants and animals directly, other bacteria can change nitrites into nitrates—a form that is usable by plants and animals. This reaction provides energy for the bacteria engaged in this process. The bacteria that we are talking about are called Nitrosomonas and Nitrobacter. Nitrobacter turns nitrites into nitrates; Nitrosomonas transform ammonia into nitrites. Both kinds of bacteria can act only in the presence of oxygen, O_2 (Manahan, 2010). The process of nitrification is important to plants, as it produces an extra stash of available nitrogen that can be absorbed by the plants through their root systems.

Stage 4: Immobilization

The fourth stage of the nitrogen cycle is immobilization, sometimes described as the reverse of mineralization. These two processes together control the amount of nitrogen in soils. Just like plants, microorganisms living in the soil require nitrogen as an energy source. These soil microorganisms pull nitrogen from the soil when the residues of decomposing plants do not contain enough nitrogen. When microorganisms take in ammonium (NH_4^+) and nitrate (NO_3^-), these forms of nitrogen are no longer available to the plants and may cause nitrogen deficiency, or a lack of nitrogen. Immobilization, therefore, ties up nitrogen in microorganisms. However, immobilization is important because it helps control and balance the amount of nitrogen in the soils by tying it up or immobilizing the nitrogen, in microorganisms.

Stage 5: Denitrification

In the fifth stage of the nitrogen cycle, nitrogen returns to the air as nitrates are converted to atmospheric nitrogen (N_2) by bacteria through the process we call denitrification. This results in an overall loss of nitrogen from soils, as the gaseous form of nitrogen moves into the atmosphere, back to where we began our store.

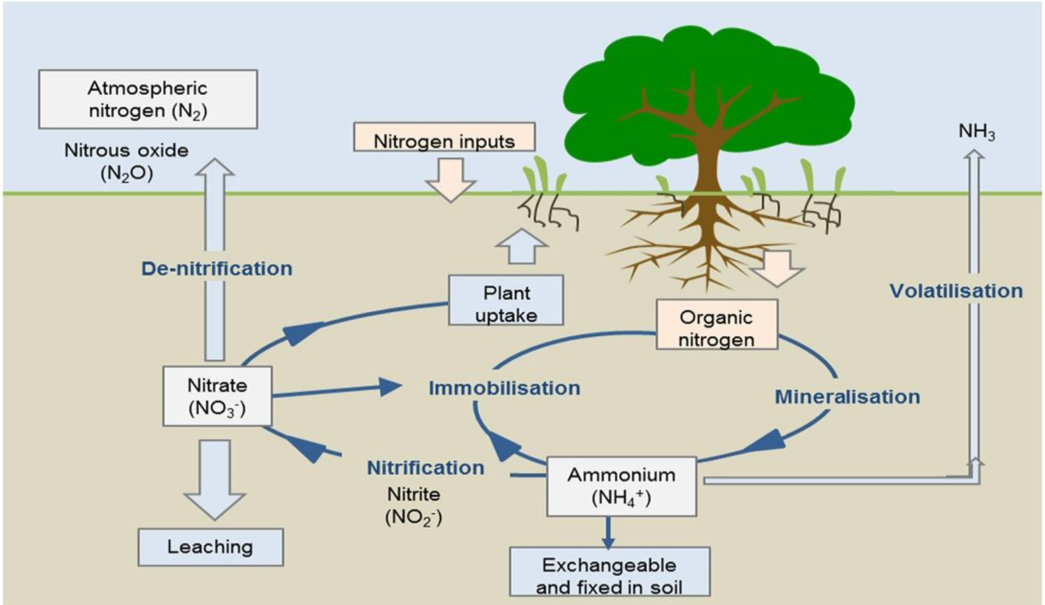

Figure 2: Nitrogen cycle

Nutrient Use Efficiency

Nitrogen use efficiency is a term used generically in the agronomic literature. Nutrient use efficiency refers not only to the ability of crops to absorb nutrients, but also to their capacity to be used, and can therefore be defined in terms of production outputs relative to nutrient inputs or in terms of recovery of applied nutrients (Baishya, 2017). An increase in NUE rates implies rational management of nutrients by the farmer to increase the efficiency of his resources, being more respectful of the environment while improving his economic profitability (Reetz, 2016). Many crop management practices can help reduce pollution from N fertilizers. The International Plant Nutrition Institute, the International Fertilizer Industry Association, the Fertilizer Institute, and the Canadian Fertilizer Institute have developed a framework for sustainable fertilizer management called "4R Nutrient Management". This framework is being implemented worldwide and synthesizes good practices in the field of fertilization in using the right nutrient source, applied at the right rate, at the right time, and in the right place, to achieve improved sustainability. These techniques are the basis of the Best Management Practice (BMP) that also includes other practices aimed at reducing diffuse pollution such as buffer strips capable of retaining the N concentrations not absorbed by crops (Baulch *et al.*, 2019); cover crops (Hefner *et al.*, 2020); use of varieties that are genetically more efficient in the use of N (Ferrante *et al.*, 2017); increasing inappropriate crop rotations (Shi *et al.*, 2019); soil tillage systems (Tei *et al.*, 2020); fertilization strategies based on soil analysis (Thompson *et al.*, 2020); methods based on N analysis in plant analysis (Padilla *et al.*, 2020) or dynamic computer simulation and decision support system (Gallardo *et al.*, 2020).

CONCLUSIONS

Of all the essential nutrients, nitrogen is required by plants in the largest quantity and is most frequently the limiting factor in crop productivity. The nitrogen cycle is a biogeochemical process through which nitrogen is converted into many forms, consecutively passing from the atmosphere to the soil to organisms and back into the atmosphere. The cycling of nitrogen through the ecosystem is crucial for maintaining productive and healthy ecosystems with neither too much nor too little nitrogen. Plant production and biomass (living material) are limited by the availability of nitrogen. Understanding how the plant-soil nitrogen cycle works can help us make better decisions about what crops to grow and where to grow them, so we have an adequate supply of food. Knowledge of the nitrogen cycle can also help us reduce pollution caused by adding too much fertilizer to soils. Certain plants can uptake more nitrogen or other nutrients, such as phosphorous, another fertilizer, and can even be used as a "buffer," or filter, to prevent excessive fertilizer from entering waterways.

According to many researchers, not enough nitrogen in the soil leaves plants hungry, while too much of a good thing can be bad: excess nitrogen can poison plants and even livestock. Pollution of our water sources by surplus nitrogen and other nutrients is a huge problem, as marine life is being suffocated from the decomposition of dead algae blooms. Farmers and communities need to work to improve the uptake of added nutrients by crops and treat animal manure waste properly. Also, it needs to protect the natural plant buffer zones that can take up nitrogen runoff before it reaches water bodies. But, our current patterns of clearing trees to build roads and other construction worsen this problem, because there are fewer plants left to uptake excess nutrients. It's better to do further research to determine which plant species are best to grow in coastal areas to take up excess nitrogen. Also, thinking to find other ways to fix or avoid the problem of excess nitrogen spilling over into aquatic ecosystems. By working toward a more complete understanding of the nitrogen cycle and other cycles at play in Earth's interconnected natural systems, we can better understand how to better protect our ecosystem safely.

Key Points

- Nitrogen is required for all organisms to live and grow because it is the essential component of DNA, RNA, and protein. However, most organisms cannot use atmospheric nitrogen, the largest reservoir.
- Nitrogen is a common limiting nutrient in nature and agriculture. A limiting nutrient is a nutrient that's in the shortest supply and limits growth.
- The five processes in the nitrogen cycle – fixation, uptake, mineralization, nitrification, and denitrification – are all driven by microorganisms.
- Humans influence the global nitrogen cycle primarily through the use of nitrogen-based fertilizers.
- Nitrogen use efficiency should be calculated as the ratio between the N removal with the harvested crops and the N input as mineral fertilizer.

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