

Nitrogen Cycling and its Dynamics in Soil-Plant Systems, Future Perspective and Research Directions: A Comprehensive Review

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ARTICLE INFO	ABSTRACT
Article History: Received: August 20, 2025 Revised: September 24, 2025 Accepted: October 14, 2025 Available Online: October 30, 2025	Nitrogen is an important macronutrient that is essential for plant growth, soil fertility and agricultural productivity. It plays a crucial role in many physiological processes including protein synthesis, photosynthesis and overall plant metabolisms. However, in agricultural systems nitrogen availability is greatly influenced by complex biogeochemical processes such as nitrogen fixation, mineralization, nitrification and denitrification that depends on microbial activity and environmental conditions. Overuse of fertilizers is a major nitrogen mismanagement practice leading to environmental problems like greenhouse gases emissions, groundwater pollution and also deteriorate soil health. This study aims to provide a comprehensive review of nitrogen dynamics in soil-plant systems, focusing on the processes regulating nitrogen availability and uptake. It explores the role of soil properties, microbial interactions and various agronomic practices in the nitrogen cycle that highlights the environmental impacts of nitrogen losses and will provide strategies to improve nitrogen use efficiency (NUE). Furthermore, it discusses sustainable management practices including the use of nitrogen-fixing crops, precision agriculture and encourage the use of some emerging techniques such as use of nano-fertilizers, microbial inoculants, AI driven- nitrogen application and carbon based nitrogen stabilizers to enhance the crop productivity while minimizing environmental degradation.
Keywords: Nitrogen cycle, nitrogen fixation, nitrogen use efficiency (NUE), soil fertility, sustainable agriculture	
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Introduction

Nitrogen (N) is a macronutrient that is important for the plant growth and soil productivity (Raina and Mazhar, 2022). It plays essential role in different biochemical and physiological processes of plants (Hawkesford et al., 2023). Therefore, nitrogen availability is directly proportional to plant growth and yield as well as for ecosystem functioning (Saleem et al., 2023). In agricultural systems, plants require adequate amount of nitrogen during their vegetative stage and reproductive stage to sustain their optimal growth. Its unavailability or imbalance can ultimately leads to nutrient deficiencies, excessive use of chemical fertilizers and environmental pollution (Ladha et al., 2022).

The nitrogen cycle is a key biogeochemical process regulating nitrogen transformations in the environment (Xia et al., 2018). This process involves different microbes and different chemical processes that convert the unavailable forms of nitrogen into plant available forms (Yang et al., 2021). Several processes such as nitrogen fixation, nitrification, denitrification and mineralization are involved in nitrogen cycle that helps the plant to uptake adequate amount or concentrations of nitrogen (Hirsch and Mauchline, 2015). Nitrogen fixation is a process in which atmospheric nitrogen is fixed by specific nitrogen fixing bacteria and is converted into ammonia (NH_3) then it is converted into ammonium (NH_4^+) in soil (Luo et al., 2024). By the process of nitrification this ammonium (NH_4^+) is converted into nitrite (NO_2^-) and nitrate (NO_3^-) forms that are easily available forms to plants (Xie et al., 2022). On the other hand, denitrification is a process in which microbes reduce this nitrate form into atmospheric nitrogen gases N_2 and N_2O that simply release in environment (Coyne et al., 2018). While, mineralization is the microbial conversion of organic nitrogen into plant available inorganic forms. Overall, this process regulate the nitrogen availability in soil and plants (Grzyb et al., 2021).

In agricultural systems, nitrogen has utmost importance because it directly affects the soil fertility and plant growth (Leghari et al., 2016). Application of nitrogen fertilizers is very common agricultural practice to replenish the soil nitrogen that has been uptake by crops, particularly in high demanded cereals, vegetables and legumes (Tei et al., 2020). However, the over application and mismanagement of these inorganic nitrogen fertilizers can lead towards environmental problems such as release of nitrous oxide gas in atmosphere that is a major greenhouse gas, eutrophication in surface water bodies and ground water pollution by leaching of nitrogen (Dimkpa et al., 2020). Therefore, nitrogen management in agricultural systems is a critical area for research. Enhancing crop productivity while minimizing environmental degradation requires improved nitrogen use efficiency (NUE) (Yadav et al., 2017).

The aim of this review is to provide an inclusive study of nitrogen dynamics in soil and plant systems for agricultural productivity and soil health. This will explore that how nitrogen cycle and the microbes influence the nitrogen availability in soil and plants including addition of fertilizers, cover cropping and crop rotation. Ultimately, the paper aims to enhance understanding of nitrogen cycling, optimize management practices and promote sustainable agriculture that improves productivity, protects soil health and reduces environmental impact.

Nitrogen Cycle in Soil-Plant Systems

The nitrogen cycle in soil-plant systems is a vital biogeochemical process that transforms nitrogen into forms accessible to plants and microorganisms as shown in figure 1.

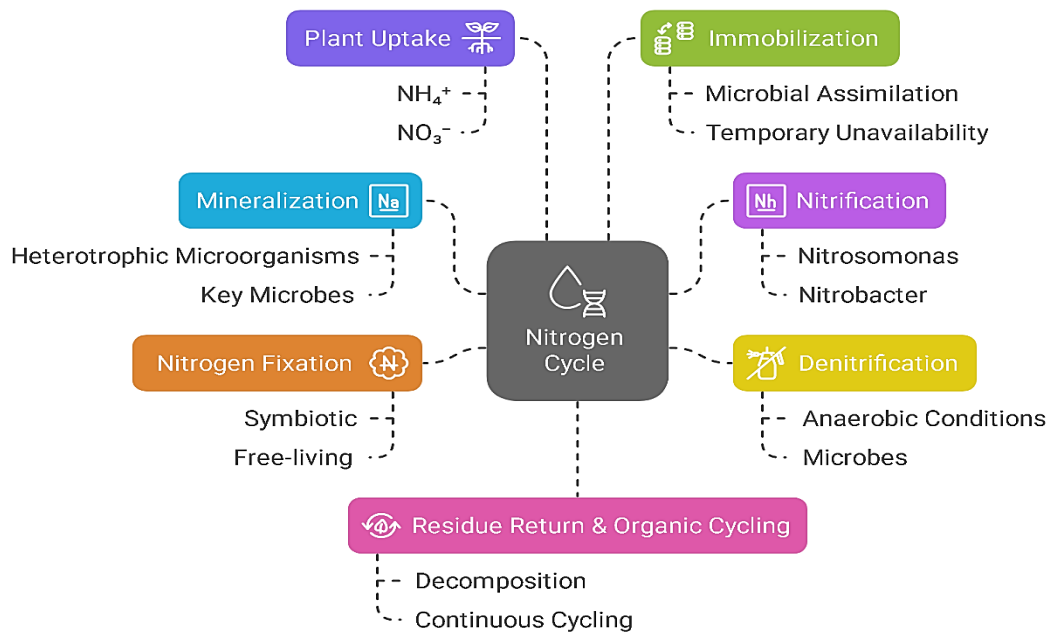


Figure 1. Nitrogen Cycle in Soil-Plant System

Mechanisms and Key Transformations

The nitrogen cycle is a complex biogeochemical process that regulates the transformation and availability of nitrogen in environment (Robertson and Groffman, 2024). Nitrogen has different forms and thus each form is responsible for different functions in plant nutrition and proper functioning of ecosystems (Paul, 2016). Mostly, it is present in soil in the form of ammonium (NH_4^+) and nitrate (NO_3^-) (Luo et al., 2024). These forms undergoes different transformations with the help of mineralization, nitrification and denitrification processes which overall influence the plant growth and soil health and productivity as presented in figure 1 (Lyu et al., 2024). Below, in Table 1 we discuss the key mechanisms and transformations in nitrogen cycle.

Mineralization

Mineralization also called as ammonification is a process in which microbes convert organic nitrogen compounds like amino acids, proteins and nucleic acids that are present in plant and animal residues into inorganic nitrogen forms such as ammonia (NH_4^+) (Das et al., 2022). This process involves soil microbes specifically bacteria and fungi during organic matter decomposition (Paul, 2016). These soil microbes convert the organic nitrogen into inorganic form ammonium that can be easily uptake by plants and can be transformed in other forms (Grzyb et al., 2021). Temperature, moisture, and soil organic matter regulate nitrogen availability and maintain soil fertility (Javed et al., 2022). Mineralization is the primary source of nitrogen in the form of ammonium as it is the very first step of nitrogen cycle. The rate of mineralization process depends on environmental conditions such as temperature and moisture content, higher the temperature and moisture higher will be the rate of mineralization process (Marzi et al., 2020).

Nitrification

Nitrification is a two-step aerobic process that helps to convert ammonium (NH_4^+) into nitrate (NO_3^-) (Wang et al., 2023). In this process, first step is the oxidation of (NH_4^+) into (NO_2^-) with the help of ammonium oxidizing bacteria such as *Nitrosomonas* species (Yan et al., 2024). The second step is oxidation of nitrite into nitrate by nitrite oxidizing bacteria such as *Nitrobacter*

species (Nowka et al., 2015). Nitrification plays a vital role in many ecological and agricultural aspects as it provides nitrate (NO_3^-) to plants that is essential for plant growth (Wang et al., 2023). However, process of nitrification leads to release of (H^+) ions that can cause soil acidification ultimately affecting the soil pH, nutrient availability and soil microbes (Dai et al., 2017). Moreover, nitrification has environmental impacts as nitrates present in soil are highly mobile and can cause groundwater pollution by the process of leaching (Bibi et al., 2016).

Denitrification

Denitrification is a process in which nitrate (NO_3^-) is converted to atmospheric forms of nitrogen such as nitrous oxide (N_2O) and nitrogen gas (N_2) by the process of reduction (Lin and Hernandez-Ramirez, 2020). This process involves soil anaerobic bacteria such as *Pseudomonas*, *Paracoccus* and *Bacillus* species that convert nitrate into nitrogen in the absence of oxygen (Grzyb et al., 2021). The process of denitrification plays a crucial role in removing the surplus nitrate from the soils by preventing its accumulation that can cause environmental problems (Wang et al., 2019). However, denitrification cause release of nitrous oxide (N_2O) that is a major greenhouse gas contributing in global warming (Jain et al., 2015). The rate of denitrifications can be affected by temperature, moisture, soil oxygen levels and nitrate availability (Cameron et al., 2013).

Table 1: Mechanisms and Key Transformations in the Nitrogen Cycle

Process	Biochemical Mechanism	Microbial Involvement	Ecological Significance	Environmental Concerns
Mineralization	Breakdown of organic nitrogen (proteins, amino acids) into ammonium (NH_4^+) via microbial decomposition (Grzyb et al., 2021).	Soil bacteria such as <i>Bacillus subtilis</i> and <i>Aspergillus niger</i> fungi (Paul, 2016)	Primary source of inorganic nitrogen and maintains soil fertility (Paul, 2016).	Influenced by soil temperature, moisture and organic matter content (Marzi et al., 2020).
Nitrification	Two-step oxidation: $\text{NH}_4^+ \rightarrow \text{NO}_2^-$ (via <i>Nitrosomonas</i>) and $\text{NO}_2^- \rightarrow \text{NO}_3^-$ (via <i>Nitrobacter</i>) (Wang et al., 2023).	Ammonium-oxidizing & nitrite-oxidizing bacteria like <i>Nitrosomonas europaea</i> (Yan et al., 2024)	Provides nitrate (NO_3^-) that is essential for crop productivity (Dai et al., 2017).	Leads to soil acidification as well as increases the nitrate leaching risk (Bibi et al., 2016).
Denitrification	Reduction of NO_3^- to gaseous forms of nitrogen (N_2O , N_2) in anaerobic conditions (Lin and Hernandez-Ramirez, 2020)	<i>Pseudomonas</i> , <i>Paracoccus</i> , <i>Bacillus</i> (Grzyb et al., 2021).	Prevents excess nitrate accumulation in soil and regulates the nitrogen balance (Cameron et al., 2013).	Contributes in greenhouse gas emissions (N_2O) (Jain et al., 2015).

Role of Ammonium (NH₄⁺) and Nitrate (NO₃⁻) in Nitrogen Availability

Nitrogen is available to the plants in the form of Ammonium (NH₄⁺) and nitrate (NO₃⁻) (Di et al., 2024). Plants absorb ammonium through active transport which is positively charged and can be uptake by roots and converted into amino acids and proteins (Muratore et al., 2021). So, high concentrations of ammonium in soil can cause soil acidification and thus, can also affect the process of nitrification that converts the ammonium into nitrate (Wang et al., 2020). Nitrate is the most mobile form of nitrogen that can be easily uptake by the plants with the help of specific transporters and then reduced into ammonium before converting into amino acids and proteins (Li et al., 2013). It is highly water soluble and that's why it can cause ground water pollution by leaching in the areas that have high rainfall and high use of inorganic fertilizers (Rashmi et al., 2020). Ammonium and nitrate balance can be influenced by pH of soil, soil microbial activity and management of fertilizer application (Neina, 2019). Acidic soils are more favourable for ammonium while neutral and alkaline soils are more suitable for nitrate (Pahalvi et al., 2021). So, that's why, plant growth is greatly affected by these nitrogen forms, high ammonium concentrations can cause toxicity while presence of adequate amount of nitrate can generally promotes the plant nutrition (Ahmed et al., 2020).

Nitrogen Fixation in Soil-Plant Systems

Nitrogen fixation is one of the important process for nitrogen replenishment in plant growth and development especially in nitrogen limiting ecosystems (Kebede, 2021). Biological nitrogen fixation is the process that can be carried by microbes having the enzyme called *nitrogenase* that converts the atmospheric nitrogen into plant available forms (Bellenger et al., 2020). Symbiotic and free living nitrogen fixation are the processes that significantly contributes in nitrogen dynamics in soil-plant systems (Smercina et al., 2019).

Free living nitrogen fixation and symbiotic nitrogen fixation

Biological nitrogen fixation plays an important role in soil-plant nitrogen systems that can be done by specific bacteria and *Archea* that helps to convert atmospheric nitrogen into ammonium (Chamoli et al., 2024). Mostly these microbes are *Rhizobia* that forms symbiotic relationship with leguminous plants such as peas, clover and beans (Wang et al., 2019). These *Rhizobia* release particular enzyme called as *Nitrogenase* that convert the nitrogen gas into ammonia (Choudhary and Verma, 2017). In this process *Rhizobia* make colonies in the roots of plants and by specialized nodulation they fix the nitrogen (Chamoli et al., 2024). These leguminous plants provides the essential growth nutrients such as carbohydrates and suitable environment and in exchange microbes do nitrogen fixation and convert it in the form of ammonia (Raza et al., 2020). Then, this ammonia is converted into amino acids and proteins and thus this symbiotic relationship between plant and microbes benefits both of them (Naik et al., 2019). This process is specie specific and energy intensive making it more effective for improving the soil nitrogen content and reducing the need of using inorganic fertilizers (Hirsch and Mauchline, 2015).

In soil nitrogen dynamics symbiotic nitrogen fixation plays a crucial role. Microbial species such as *Azotobacter*, *Clostridium*, *Frankia* and certain *cyanobacteria* can fix the nitrogen without any host plant (Mishra et al., 2021). These microbes live in soil or in water and convert atmospheric nitrogen into ammonium and other nitrogen forms (Robertson and Groffman, 2024). Although, the nitrogen they fix is not directly transferred to plants through symbiosis, it still contributes to the overall nitrogen pool in the soil (Mahmud et al., 2020). Nitrogen become available to the plants when these microbes die and thus nitrogen become plant available (Naik et al., 2019). Mostly, free living nitrogen fixing microbes live in nutrient poor environment where they provide nitrogen and

improves the soil conditions (Mishra et al., 2021). *Cyanobacteria* are the free living bacteria that fix nitrogen in the presence of sunlight for photosynthesis (Issa et al., 2014). Both free-living and symbiotic nitrogen fixers play significant role in improving the soil nitrogen levels and thus enhance the plant growth as well as soil health as presented in figure 2 (dai et al., 2024). The combined action of symbiotic and free-living nitrogen fixers helps to maintain a dynamic nitrogen cycle in soil, fostering sustainability in agricultural and natural ecosystems (Nawaz et al., 2024).

Characteristic	Symbiotic Microbes (Rhizobia)	Free-Living Microbes (Azotobacter, Clostridium, Frankia, Cyanobacteria)
Relationship	Mutualistic	Non-symbiotic
Host	Leguminous plants	None
Location	Root nodules	Soil and water
Nitrogenase	Yes	Yes
Contribution	Direct	Indirect

Figure 2: Comparison of Symbiotic and Free-Living Microbes.

Nitrogen uptake by plants

Nitrogen is essential for plant growth and development so its uptake is one of the vital plant process (Leghari et al., 2016). Plants absorb nitrogen in different forms such as ammonium (NH_4^+) and nitrate (NO_3^-) that are result of nitrogen cycle (nitrogen fixation, mineralization and nitrification) in soil (Luo et al., 2024). These processes can be influenced by transport mechanisms present in plant root system and different environmental conditions therefore, can affect the nitrogen uptake and ultimately affect the plant growth and development (Muratore et al., 2021).

Mechanisms of nitrogen uptake (Root Assimilation)

Plants absorb nitrogen in different forms from the soil and each nitrogen form has different uptake root mechanism (Wang et al., 2024). Ammonium is absorbed by proteins transporters that work efficiently in acidic soils having low nitrogen availability and low pH (Muratore et al., 2021). Once ammonium is uptake by plants with the help of enzyme called *glutamine synthetase* it converts into other nitrogen compounds as well as helps in protein synthesis (Taria et al., 2022). On the other side, nitrate is taken up with the help of nitrate transporters and are more dominant in high pH or alkaline soils (Geng et al., 2021). After its uptake, nitrate is transported through the plant's vascular system, reduced to ammonium by nitrate reductase and assimilated into amino acids and other nitrogen compounds. This process is controlled by nutrient sensing transporters that regulate the nitrogen levels in soil when nitrogen is scarce or abundant (Aluko et al., 2023).

Interactions with other nutrients and factors affecting uptake efficiency

The nitrogen uptake efficiency in plants can be influenced by biochemical, physiological and environmental factors (Sandhu et al., 2021). Different essential nutrients such as potassium, magnesium, phosphorous, sulphur and calcium interact with the nitrogen uptake and helps in performing various functions for plant growth (Ahmed et al., 2020). Nitrogen uptake can increase the phosphorous uptake that helps in protein and nucleic acid synthesis (Raven, 2015). Similarly, sulphur also helps in protein synthesis and marinating nitrogen metabolisms. Potassium helps in enzyme activation and nitrogen assimilation while calcium and magnesium improves the cell

structure and enzyme functioning (Shah et al., 2022). Some nutrients and soil factors that influence the nitrogen uptake efficiency in plants are discussed in Table 2.

Soil pH is one of the significant factor that greatly affects the nutrient uptake. Ammonium mostly dominates in acidic soils while, alkaline soils are favourable for nitrate (Neina, 2019). Neutral pH like 6-7 are best for optimal nitrogen absorption. Soil microbial activity also enhance the nitrogen availability by providing suitable environment for the processes like nitrogen fixation and nitrification (Grzyb et al., 2021). Additionally, the plant's developmental stage affects the nitrogen uptake efficiency with different growth stages demanding varying nitrogen amounts to support root growth, flowering and fruit development (Kubar et al., 2022).

Table 2: Nutrient interactions and some soil factors that influence the nitrogen uptake efficiency in plants

Nutrient Interactions	Influence on Nitrogen Uptake	Reference
Potassium (K)	Enhances enzyme activation and nitrogen assimilation	Shah et al., 2022
Magnesium (Mg)	Improves cell structure and enzyme functioning	Shah et al., 2022
Phosphorous (P)	Increases nitrogen uptake, aiding in protein and nucleic acid synthesis	Raven, 2015
Sulphur (S)	Supports protein synthesis and nitrogen metabolism	Ahmed et al., 2020
Calcium (Ca)	Enhances cell structure and enzyme functionality	Shah et al., 2022
Soil Factors		
Soil pH	Acidic soils favour ammonium uptake, alkaline soils favour nitrate absorption	Neina, 2019
Microbial Activity	Supports nitrogen availability through nitrogen fixation and nitrification	Grzyb et al., 2021

Efficiency of Nitrogen Use

The efficiency of nitrogen use is vital for plant nutrition and sustainable agriculture. Balanced nitrogen uptake is important for optimal plant growth and development (Wang et al., 2022). Plants are more able to produce high yields when the nitrogen uptake is efficient without the application of inorganic fertilizers that not only affect the nutrient efficiency but also have environmental impacts such as leaching and emission of greenhouse gases (Asadu et al., 2024). The efficiency of nitrogen uptake depends on different factors such as plant genetic capacity, soil conditions (pH, moisture and nutrient availability) and management practices such as crop rotation and fertilizer application (Yadav et al., 2017).

To improve the nitrogen use efficiency (NUE) strategies such as precise agriculture, fertilizer application management and promoting nitrogen fixing crops should be employed (Govindasamy et al., 2023). For instance, Table 3 describes some rotating nitrogen-fixing legumes that can reduce the need for synthetic fertilizers and enhance soil nitrogen content, thereby improving nitrogen uptake efficiency in subsequent crops (Kebede, 2021).

Table 3: Some rotating nitrogen fixing legumes crops and their role in nitrogen cycling and soil-plant systems

Legume Crop	Role in Nitrogen Cycling	Impact on Soil-Plant Systems	References
Alfalfa	Fixes atmospheric nitrogen (N ₂) through symbiotic rhizobia, adding 100-300 kg N/ha/year to the soil.	Improves soil fertility, reduces the need for synthetic fertilizers, and enhances subsequent crop yields.	(Russelle, 2001)
Soybean	Fixes 50-250 kg N/ha/year, contributing to soil nitrogen pools and reducing nitrogen fertilizer requirements.	Enhances soil organic matter, improves soil structure, and supports sustainable crop rotations.	(Salvagiotti et al., 2008)
Clover	Fixes 50-200 kg N/ha/year, enriching soil nitrogen and supporting intercropping or cover cropping systems.	Suppresses weeds, prevents soil erosion, and improves soil health through organic matter addition.	(Crews and Peoples, 2004)
Faba beans	Fixes 50-150 kg N/ha/year, contributing to nitrogen availability for subsequent crops.	Improves soil nitrogen content, supports crop diversification, and reduces greenhouse gas emissions from fertilizers.	(Jensen et al. 2010)
Lentils	Fixes 50-150 kg N/ha/year, enhancing soil nitrogen levels and supporting sustainable farming practices.	Improves soil fertility, reduces nitrogen leaching, and promotes biodiversity in agroecosystems.	(Gan et al. 2015)
Beans	Fixes 30-100 kg N/ha/year, contributing to soil nitrogen pools and reducing dependency on synthetic fertilizers.	Enhances soil organic carbon, improves water retention, and supports food security in smallholder farming systems.	(Jansa et al., 2011)
Chickpeas	Fixes 50-140 kg N/ha/year, improving soil nitrogen availability and supporting crop rotations.	Reduces soil degradation, enhances microbial activity, and improves soil structure.	(Kumar et al. 2023)
Faba Beans	Fixes 100-300 kg N/ha/year, significantly enriching soil nitrogen and supporting intercropping systems.	Improves soil fertility, reduces nitrogen fertilizer use, and enhances biodiversity in agricultural systems.	(Jensen and Hauggaard-Nielsen, 2003)
Cowpea	Fixes 50-200 kg N/ha/year, contributing to soil nitrogen and	Improves soil moisture retention, reduces erosion, and enhances resilience to climate change.	(Singh et al. 2003)

	supporting sustainable agriculture in arid regions.	
Groundnut (Peanut)	Groundnuts can fix between 150–200 kg N ha ⁻¹ over a growing period of 106–119 days.	Enhances soil organic matter, improves soil structure, and reduces nitrogen losses through leaching. (Witcombe and Tiemann, 2021)

Nitrogen losses in soil-plant systems and their environmental impacts

Nitrogen losses in soil-plant systems can be due to the leaching, volatilization and denitrification that reduces the nitrogen availability in plants and also significantly affect the environment (Mahmud et al., 2021). *Leaching* is the downward seepage of nitrate (NO₃⁻) due to heavy rainfall in the soils. It has low cation exchange capacity into the groundwater and thus this can results in water pollution including eutrophication of water bodies (Wang et al., 2019). *Volatilization* is the process in which ammonia gas release in the environment through alkaline soils (Li et al., 2022). Thus, this can contribute in air pollution including formation of particulate matter and acid rain that reduce the nitrogen use efficiency in agriculture systems (Das et al., 2021). While, *denitrification* is the conversion of nitrate into greenhouse gas nitrous oxide (N₂O) with the help of denitrifying bacteria under anaerobic conditions contributing in global warming (Aryal et al., 2022). These processes highlights the nitrogen losses showed in Table 4 and convince us to manage or improve the nitrogen use in agricultural systems to minimize the environmental degradation (Han et al., 2024).

Table 4. Environmental Impacts of Nitrogen Loss Pathways in Soil-Plant Ecosystems

Nitrogen loss Pathways	Mechanism	Environmental Impact	References
Volatilization	Conversion of ammonium (NH ₄ ⁺) to ammonia (NH ₃) gas, especially in high-pH soils.	Contributes to air pollution, formation of particulate matter (PM _{2.5}), and indirect N ₂ O emissions.	(Skorupka and Nosalewicz, 2021).
Leaching	Nitrate (NO ₃ ⁻) moves with water beyond the root zone into groundwater.	Contaminates drinking water, causes eutrophication in aquatic ecosystems (e.g., algal blooms).	(Das et al., 2025)
Denitrification	Microbial conversion of NO ₃ ⁻ to N ₂ O and N ₂ gases under anaerobic conditions.	N ₂ O is a potent greenhouse gas (GHG), contributing to global warming and ozone layer depletion.	(Zhao et al., 2025)
Runoff	Surface movement of NO ₃ ⁻ and NH ₄ ⁺ into water bodies.	Causes eutrophication, hypoxia (e.g., dead zones in oceans), and loss of aquatic biodiversity.	(Zhou et al., 2024)
Immobilization	Microbes temporarily tie up nitrogen in organic forms, making it unavailable.	Reduces nitrogen availability for plants, potentially leading to over-fertilization to compensate.	(Gelaye et al., 2022)
Erosion	Soil particles carrying	Loss of soil fertility, sedimentation in	(Ghaly and

Nitrous Oxide Emissions	nitrogen are washed or blown away.	water bodies, and nutrient pollution in aquatic systems.	Ramakrishnan, (2015)
	Microbial processes (nitrification and denitrification) release N ₂ O.	N ₂ O is 265x more potent than CO ₂ as a GHG, contributing significantly to climate change.	(Hui et al., 2024)
Ammonia Deposition	NH ₃ from volatilization deposits back onto land or water.	Acidification of soils and water bodies, nutrient imbalances, and damage to sensitive ecosystems.	(Samojedny et al., 2022)

Mitigating nitrogen losses and their impacts

Nitrogen losses and their impacts on environment can be minimize by adopting different strategies such as use of efficient fertilizer and soil management, using cover crops and by using precise agriculture strategies such as use of sensors and GPS systems (Swathy et al., 2024). Efficient fertilizer techniques involves application of nitrogen fertilizers at suitable dosage and at favourable times to reduce the underground leaching and volatilization (Dimpka et al., 2020). Soil management includes practices like to improve soil structure, drainage and pH that reduce the rate of denitrification and thus enhance the nitrogen use efficiency (Ullah et al., 2019). These strategies collectively aim to optimize nitrogen use while mitigating negative environmental impacts.

Factors Influencing Nitrogen Dynamics in soil and plant system

Soil properties

Soil properties have great influence on nitrogen dynamics in soil-plant systems. These soil properties includes soil pH, soil texture, organic matter content and soil microbial activity (Bashir et al., 2021). Soil pH affects the nitrogen availability like ammonium (NH₄⁺) concentrations are high in acidic soils while increased nitrate (NO₃⁻) availability is observed in alkaline soils. Soil texture also affects the water retention and nutrient leaching in soils (Khan et al., 2024). More nitrate leaching is observed in sandy soils on the other hand, clayey soils promotes waterlogging and thus enhance the rate of denitrification (Rashid et al., 2020). Organic matter application is very important in nitrogen mineralization as organic matter decomposition release nitrogen in plant usable forms. However, too much application of organic matter can cause nitrogen immobilization (Younas et al., 2022). Similarly, high soil microbial activity promotes efficient nitrogen cycling but excessive activity under anaerobic conditions can cause denitrification and nitrogen losses (Shen et al., 2022).

Climatic factors

Climatic factors also directly affect the nitrogen dynamics in soil-plant systems. Factors like temperature and rainfall play key role in nitrogen dynamics (Hoang et al., 2022). Temperature have great influence on microbial activity and thus nitrogen transformations. Rate of nitrification and mineralization can be accelerated by high temperatures and thus ammonium volatilization can be increase in alkaline soil conditions (Waqas et al., 2021). Nitrogen availability can also be affected by rainfall as it influence the soil moisture (Zhang et al., 2021). Heavy rainfall and poor irrigation practices can lead to nitrate leaching while low rainfall can affect the nitrogen uptake by plants. Similarly, water logging conditions in anaerobic environment can promotes denitrification leading to nitrogen loss in the form of nitrous oxide (N₂O) (Abid et al., 2024).

Crop type and management practices

Crop type and management practices significantly affects the nitrogen dynamics (Lassaletta et al., 2021). Different crop types such as leguminous and non-leguminous determine nitrogen requirements (Xiao et al., 2025). Leguminous crops can increase the soil nitrogen by fixing nitrogen and making symbiotic relationship while non-leguminous crops rely on external nitrogen sources (Kebede, 2021). Misapplication of nitrogen fertilizers either organic or inorganic can cause leaching, volatilization and denitrification (Yadav et al., 2023). Sustainable practices such as crop rotation and intercropping with nitrogen-fixing plants help maintain soil nitrogen levels and reduce dependency on external fertilizers, improving nitrogen use efficiency and reducing environmental impacts (Chen et al., 2024).

Nitrogen management in agriculture

Effective nitrogen management practices in agriculture are essential in enhancing soil properties, crop productivity and in minimizing environment degradation (Hussain et al., 2021). Proper fertilizer management, including precise timing and the use of slow-release fertilizers, can enhance the nitrogen use efficiency and minimize nitrogen losses through leaching, volatilization and denitrification (Gautam et al., 2022). Agronomic practices like crop rotation, cover cropping and optimized irrigation are essential for maintaining soil nitrogen levels and mitigating nitrogen loss (Mahmud et al., 2021). Overall, a comprehensive approach to nitrogen management which combines soil, microbial and agronomic strategies, is key to achieving sustainable agricultural productivity while reducing environmental impact (Harindintwali et al., 2021).

Challenges in managing nitrogen dynamics

In agricultural systems, effective nitrogen management has many challenges because of significant nitrogen losses, poor nitrogen use efficiency and climate change fluctuations. Innovative and holistic approaches are required to optimize the nitrogen use while reducing the environmental impact.

Nitrogen use efficiency and its limitations

Nitrogen use efficiency (NUE) is the term usually refers the ability of plants to utilize the available nitrogen for their growth. Regardless of the high use of nitrogen fertilizers in many agricultural systems NUE still remains low because of nitrogen losses by leaching, volatilization and denitrification (Anas et al., 2020). One of the major mismanagement in agricultural systems is the nitrogen application methods and timing that actually affects the effective nitrogen availability of plants (Sharma and Bali, 2017). In-effectiveness of inorganic fertilizers is also a major problem that does not meet the plant demands during growth season and thus results in nitrogen losses (Chen et al., 2018). Several soil properties such as soil texture, pH, soil microbial activity and nutrient uptake capacity of plants also bound the NUE (Zhang et al., 2019). Overcoming these limitations requires better understanding and management of nitrogen dynamics in the soil-plant system, as well as adopting more sustainable and efficient fertilization strategies.

Nitrogen losses in intensive agricultural systems

In intensive agricultural systems, it is a common practice to use large quantities of nitrogen fertilizers that often results nitrogen losses through nitrate leaching, ammonia volatilization and denitrification leading to environmental pollution (Wang and Li et al., 2019). Leaching of nitrate leads to groundwater contamination that results in eutrophication. Ammonia volatilizations results in the formation of particulate matter resulting in air pollution (de Vries et al., 2023). Release of

nitrous oxide (a greenhouse gas) from denitrification is also contributing in global warming. To cope with these nitrogen losses, integrated management strategies like precise fertilization, cover cropping and use of slow release fertilizers needs to be used to ensure nitrogen availability to plants without any nutrient loss (Aryal et al., 2022).

Impacts of climate change on nitrogen cycling

Climate change has significant role in nitrogen cycling in soil-plant systems. Increase in temperature can enhance the microbial activity that can accelerate the rate of nitrification and mineralization (Farooq et al., 2022). It can also leads increase in ammonia volatilization and denitrification. Extreme weather conditions such as increase in rainfall and flooding may cause waterlogging leading towards anaerobic conditions that favour denitrification that cause nitrogen loss in the form of nitrous oxide (N₂O) (Gimire et al., 2020). Furthermore, change in precipitation patterns can also alter the nitrogen leaching dynamics leading towards groundwater contamination (Wang and Li, 2019). Droughts also hinder the NUE by affecting the plant nitrogen uptake. To mitigate these impacts, adaptive nitrogen management strategies such as regulation in fertilizer application timing, use of more resilient crop varieties and soil health improvement practices are required for sustainable agricultures (Zhu et al., 2022).

Emerging technologies for nitrogen management

Some of these emerging techniques may include the use of nano-fertilizers, microbial inoculants, AI driven nitrogen application, carbon based nitrogen stabilizers etc. Aims of these approaches are to increase nitrogen use efficiency (NUE), reduced environmental impacts and improving sustainable agriculture. Comparison summary of these approaches also presented in figure 3.

Use of Nano-fertilizers

Nanotechnology provides innovative nitrogen management by using nanoparticles to optimize controlled fertilization of plants in a precise way. Using nano fertilizers minimizes losses of nitrogen from the soil as they reduce the typical problems of leaching, volatilization and denitrification that affect regular fertilizers (Liu and Lal, 2015). Nano fertilizers possess the capability to direct nutrients toward plant tissues by design as well as release nutrients whenever triggered by environmental signals like moisture or pH (Rajamuthuramalingam et al., 2024). Nano fertilizers elevate nitrogen use efficiency (NUE) and boost yield production along with lowering environmental degradation processes (Mejías et al., 2021). The research on nano-urea shows promising results because this technique improves nitrogen absorption in wheat and rice crops thereby minimizing traditional urea requirements with their negative consequences.

Use of microbial inoculants

Plant growth-promoting rhizobacteria (PGPR) along with nitrogen-fixing bacteria *Rhizobium* and *Azospirillum* are beneficial microorganisms used as microbial inoculants to improve soil nitrogen availability (Bhattacharyya and Jha, 2012). The microbes establish symbiotic relationship with plants specifically with legumes to transform atmospheric nitrogen into usable forms for plants (Pankievicz et al., 2019). Non leguminous plants also show better nitrogen uptake with microbial inoculations, these boost their root expansion and nutrient acquisition mechanisms. The microbes produce growth-stimulating compounds and simultaneously generate substances that protect plants from soil-borne infections (Jalal et al., 2022). Microbial inoculants change farming systems toward sustainability by offering resistance against synthetic fertilizers and they maintain environmental health and agricultural practices (Miteu et al., 2022).

Use of AI driven nitrogen application

Artificial intelligence (AI) along with machine learning operates through precision agriculture systems to benefit modern nitrogen management practices. Artificial Intelligence technology extracts real-time moisture data from soil sensors and weather data and crop health data to calculate the most effective time for nitrogen application (Assimakopoulos et al., 2025). The system provides accurate nitrogen fertilizer placement at exact crop sites at determined time points. Implementing this method leads to reduced nitrogen waste together with lower pollution levels similar to greater crop production (Swathy et al., 2024). Use of AI-based systems that support farms result in improved wheat and maize cultivation through advanced nitrogen management techniques that simultaneously boost the use of nitrogen better while decreasing emissions of greenhouse gases. AI devices that operate with drone technologies and satellite systems maintain accurate performance levels while increasing system capabilities (Mana et al., 2024).

Carbon based nitrogen stabilizers

Soil stabilization of nitrogen relies on applications of carbon-based products including biochar and activated carbon that minimize nitrogen loss through leaching and volatilization processes. The carbon-rich product biochar reaches high levels of surface area and porosity through its production from organic waste (pyrolysis) therefore it successfully adsorbs and stores nitrogen compounds (Cayuela et al., 2014). The use of biochar allows the more carbon sequestration in soil which decreases atmospheric CO₂ concentrations thus mitigating climate change effects. Its application brings two essential benefits including reduction of greenhouse gas emissions while simultaneously improving land fertility and crop yields (Shoudho et al., 2024).

Use of enhanced efficiency fertilizers

The main function of Enhanced efficiency fertilizers (EEFs) involves controlled nitrogen release combined with processes inhibition which improves nitrogen use efficiency. The fertilizers receive polymer coatings or integrated inhibitors which reduce nitrogen expiration and stop its natural transformation into environmental loss forms (Dimpka et al., 2020). Nitrification inhibitors are responsible of slowing down the ammonium to nitrate conversion process thus decreasing leaching and denitrification losses of nitrogen. Urease inhibitors stop the process of urea breakdown into ammonia (NH₃) thus minimizing ammonia volatilization (Li et al., 2023). So, the application of EEFs demonstrates effectiveness in increasing crop productivity together with decreased nitrogen losses and decreased adverse environmental effects.

Integrated soil crop system management

Integrated soil crop system management (ISSM) involves use of integrated fertilization techniques along with optimal crop rotation and the soil management practice to increase soil nitrogen cycling potential and soil environmental conditions (Li et al., 2023). Since the operational nature of ISSM requires proper nitrogen supply to increase organic matter accumulation and beneficial microbial populations, ISSM maintains proper nitrogen supply within its corresponding requirements. This procedure therefore introduces soil nitrogen preservation and in turn soil fertility and enhanced crop production (Wang et al., 2020).

Biological nitrification inhibition

Plants exhibit a natural ability to release inhibitory compounds that limit function of nitrifying bacteria thus blocking the process of NH₄⁺ to NO₃⁻ transformation in the soil. The soil preserves nitrogen through this biological process in a more stable non-leachable form which cannot be

easily lost through denitrification. Observations indicate that BNI occurs in Brachiaria grass plants through root exudate production for nitrification inhibition (Subbarao et al., 2009). Thus, the incorporation of BNI crops into agricultural fields leads to decreased nitrogen drainage combined with better nitrogen recycling efficiency.

Circular nitrogen economy

Circular nitrogen economy is a recycling of nitrogen from organic wastes (manure, crop residues and food wastes) to minimize its dependence on synthetic fertilizers. The nitrogen economy aims at reconciling resource efficiency, decreases in nitrogen waste and sustainable farming.

Furthermore, long term field experiments and studies are essential to understand the effectiveness of different nitrogen management practices according to soil type and climatic conditions. These will further help to develop the sustainable and adaptive strategies for future agricultural practices. These combined approaches aim to optimize nitrogen use, reduce environmental pollution and ensure long-term agricultural productivity.

Characteristic	Nano-fertilizers	Microbial Inoculants	AI-Driven Application	Enhanced Efficiency Fertilizers	Integrated Soil-Crop System Management	Circular Nitrogen Economy
Mechanism	Precise nutrient delivery	Fix atmospheric nitrogen	Real-time data for placement	Regulate nitrogen transformation	Crop rotation and fertilization	Recycles nitrogen from waste
Benefits	Reduces nitrogen losses	Stimulates root growth	Increases nitrogen use efficiency	Minimizes nitrogen losses	Improves soil health	Promotes sustainable resource use

Figure 3: Comparison of Nitrogen Management technologies

Conclusion

This article concludes the role of nitrogen dynamics in soil-plant systems that emphasize its contribution to soil health, plant growth and in sustainable agricultural practices. The nitrogen cycle and its different steps like nitrogen fixation, mineralization, nitrification and denitrification are mainly influence by soil properties and climatic conditions which affects the nitrogen availability and plant uptake. Efficient nitrogen management practices play critical role in improving crop productivity while minimizing the environmental impacts. Nitrogen losses by leaching, volatilization and denitrification along with climate change are the challenges in sustainable nitrogen management. This review emphasis on the importance of different strategies such as crop rotation, balanced application of fertilizer and incorporation of nitrogen fixing crops and the use of innovative technologies such as nano-fertilizers, microbial inoculants, AI driven nitrogen application, and carbon based nitrogen stabilizers.. By using these mitigation strategies it is possible to enhance crop productivity while minimizing environmental degradation. Future research directions involve exploring these advanced techniques and integration of these in current agricultural systems is needed. Long-term field studies are also needed to evaluate the effectiveness of these practices. These approaches aim to promote sustainable agricultural practices that enhance productivity while protecting the soil and reduce environmental impacts.

Author's contributions

All authors made significant contributions towards the successful writing of this work and also approved it for publication.

Competing interest

The authors disclose that they have no competing interests.

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