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Soil Nitrogen Cycling: An Indian Perspective

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ABSTRACT

Soil nitrogen cycling is a crucial aspect of nutrient management and agricultural productivity, with significant implications for food security and environmental sustainability. This paper provides a comprehensive overview of soil nitrogen cycling in India, with an emphasis on the various processes involved, the factors influencing these processes, and the implications for agricultural practices and environmental conservation.

Keywords: Soil Nitrogen Cycling, Nutrient Management, Agricultural productivity, Environmental Sustainability

INTRODUCTION

The availability of the many building blocks of life, such as essential major elements like carbon (C), nitrogen (N), and phosphorus (P); essential minor elements like iron, zinc, and cobalt; and, for many marine organisms, essential trace organic nutrients that they cannot manufacture themselves (e.g., amino acids and vitamins), is necessary for the continued production of organic matter in the sea. Because of the variety of structural and metabolic roles that these necessary nutrients play, marine creatures cannot exist without them. The Earth's hydrosphere, lithospheric, atmospheric, and biosphere nitrogen cycles are all interrelated, and the marine nitrogen cycle is only a small portion of them. Furthermore, the synthesis and remineralization of organic matter—particularly that which occurs in the vicinity of the surface ocean where phytoplankton is produced—is a crucial component of the ocean's cycles of carbon, nitrogen, and phosphorus. One way to think of this coordinated network of main bio-elements is as the nutritional "super-cycle." Dissolved gaseous dinitrogen (N_2) makes up about 95% of the total nitrogen inventory in the sea and is the predominant type of nitrogen. However, this form is almost inert due to the relative stability of the N_2 triple bond. While specialist N_2^- fixing bacteria can use N_2 as a biologically accessible nitrogen source, these species are very uncommon in most marine habitats. Therefore, the main sources of nitrogen needed to support biological processes are chemically "fixed" or "reactive" nitrogen molecules such nitrate (NO_3-), nitrate (NO_2^-), ammonium (NH_4^+), and dissolved and particulate organic nitrogen (DON/PON).

Oceanographers have been studying the identification of elements that limit growth and production rates for almost a century. This has sparked research into the marine nitrogen cycle, encompassing inventory calculations as well as the mechanisms and regulations governing nitrogen conversions across forms. Current ocean research has shown the significance of trace inorganic nutrients and the unbreakable connection between the cycles of phosphorus and nitrogen. The likelihood that nitrogen is merely one of several essential components for marine life—neither more nor less significant than the others—now seems very likely. Even though the marine nitrogen cycle's fundamentals were established about 50 years ago, new pathways and unique microbes are always being found. As such, our conceptual framework for understanding the nitrogen cycle is adaptable and ready for revision at any time.

Nitrogen in Indian Soils

This section provides an overview of the sources of nitrogen in Indian soils, including Nitrogen is an essential nutrient for plant growth and is a crucial component of proteins, enzymes, and chlorophyll. In Indian soils, nitrogen can come from various sources, including atmospheric deposition, biological nitrogen fixation, and fertilizer application.

Atmospheric Deposition: Nitrogen can enter the soil through atmospheric deposition. This can occur in the form of wet deposition (rain or snow) and dry deposition (gaseous or particulate matter). Nitrogen compounds like ammonia (NH_3), nitric oxide (NO), nitrogen dioxide (NO_2), and nitrate (NO_3^-) can be deposited from the atmosphere to the soil. The primary sources of these compounds include agricultural activities, combustion of fossil fuels, and natural processes such as lightning.

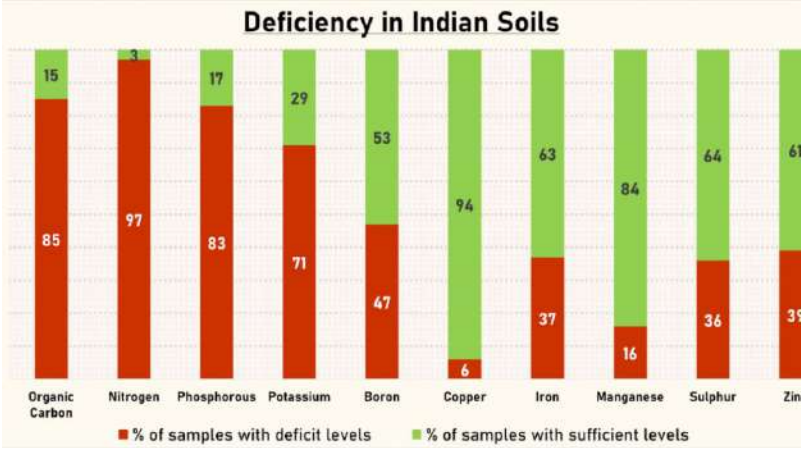

Figure 2 : Indian Soils Extremely Deficient in Nutrients

Biological Nitrogen Fixation: Biological nitrogen fixation is a process in which atmospheric nitrogen (N_2) is converted into ammonia (NH_3) by bacteria. Some bacteria can form symbiotic relationships with the roots of certain plants, most notably legumes (such as soybeans, peas, and lentils). These bacteria, known as rhizobia, live in nodules on the plant's roots and fix atmospheric nitrogen, making it available to the plant. Some free-living soil bacteria and blue-green algae can also fix atmospheric nitrogen, contributing to the nitrogen pool in the soil.

Fertilizer Application: In Indian agriculture, synthetic nitrogen fertilizers are widely used to meet the nitrogen demands of crops. These fertilizers usually contain nitrogen in the form of urea, ammonium nitrate, ammonium sulphate, or other nitrogen-containing compounds. When applied to the soil, these fertilizers release nitrogen, which can be taken up by plants. However, overuse of synthetic nitrogen fertilizers can lead to environmental problems such as soil degradation, water pollution, and greenhouse gas emissions.

Organic Matter Decomposition: Organic matter in the soil, such as plant residues and animal manure, also contributes to the nitrogen pool in the soil. As organic matter decomposes, it releases nitrogen in the form of ammonia, which can be taken up by plants or converted into other nitrogen compounds through microbial activity.

Crop Residues and Manure: Crop residues left in the field after harvest, as well as animal manure applied to the soil, can also be important sources of nitrogen. These materials break down over time, releasing nitrogen and other nutrients that can be taken up by plants.

Nitrogen Import through Irrigation: Irrigation water can also bring in nitrogen into the soil, especially if the water source is contaminated with nitrogen compounds. This can be an additional source of nitrogen for crops.

Distribution of Nitrogen in Different Soil types and Regions of India

The distribution of nitrogen in different soil types and regions of India is influenced by factors such as climate, vegetation, land use, and human activities. Here is a more detailed analysis of the distribution of nitrogen in various soil types and regions of India:

Alluvial Soils: Alluvial soils are found in the northern plains of India, including Punjab, Haryana, Uttar Pradesh, Bihar, and West Bengal. These soils are formed by the deposition of sediments brought by rivers like the Ganges and the Indus. Alluvial soils are usually rich in nutrients, including nitrogen, because of the organic matter brought by the rivers. However, intensive agriculture in these areas can lead to nitrogen depletion, and synthetic nitrogen fertilizers are commonly used to replenish soil nitrogen.

Black Soils: Black soils, also known as Regur soils or Vertisols, are found in the central and western parts of India, including Maharashtra, Madhya Pradesh, Gujarat, and parts of Andhra Pradesh and Karnataka. These soils are formed from volcanic rocks and are rich in clay minerals. Black soils have a good capacity to retain water and nutrients, including nitrogen. However, the nitrogen content can vary depending on the crops grown and the level of fertilizer application.

Red and Laterite Soils: Red and laterite soils are found in the southern and eastern parts of India, including Tamil Nadu, Karnataka, Andhra Pradesh, Odisha, and parts of West Bengal. These soils are formed from the weathering of igneous and metamorphic rocks and are rich in iron oxides, which give them their red color. Red and laterite soils generally have lower nitrogen content compared to alluvial and black soils. The nitrogen content can be further reduced by continuous cropping without proper nutrient management.

Desert Soils: Desert soils are found in the arid regions of Rajasthan and parts of Gujarat. These soils have low organic matter content and low nitrogen availability. The nitrogen content in desert soils can be further limited by high temperatures, low rainfall, and high evaporation rates.

Mountain Soils: Mountain soils are found in the Himalayan region and the hilly areas of north eastern India. These soils are formed from the weathering of rocks and have a wide range of characteristics depending on the altitude, climate, and vegetation. Mountain soils can have varying levels of nitrogen content, with higher levels in areas with dense vegetation and lower levels in areas with sparse vegetation.

PROCESSES INVOLVED IN NITROGEN CYCLING

- The biogeochemical cycle is known as the nitrogen cycle.
- About 75% of the gases in the atmosphere are nitrogen, making it a crucial component.
- Vitamins, nucleic acids, pigments, amino acids, and proteins all rely on it as a key component.
- Soil microorganisms and the roots of plants that interact with them convert atmospheric nitrogen in the soil's pore spaces into free nitrogen.

Fixation

- Fixation is the first stage in the transformation of nitrogen into a form that plants can use.
- Ammonium is often produced when bacteria convert nitrogen.

Nitrification

- This is the bacterial conversion of ammonium to nitrates.
- Nitrates are taken up by the plants.

Assimilation

- Only plants can get nitrogen through this process.
- Nitrates in the soil are taken up by their roots.
- Chlorophyll, nucleic acids, and amino acids all rely on nitrogen.

Ammonification

- This is part of the decaying process.
- Nitrogen from dead plants and animals is converted back into the nitrogen cycle as ammonium by decomposers like bacteria and fungi.

De-nitrification

- Aerating the soil releases any excess nitrogen that has accumulated there.
- In addition, there are specialized bacteria that perform this function.
- The role of soil microorganisms in facilitating these processes is highlighted.

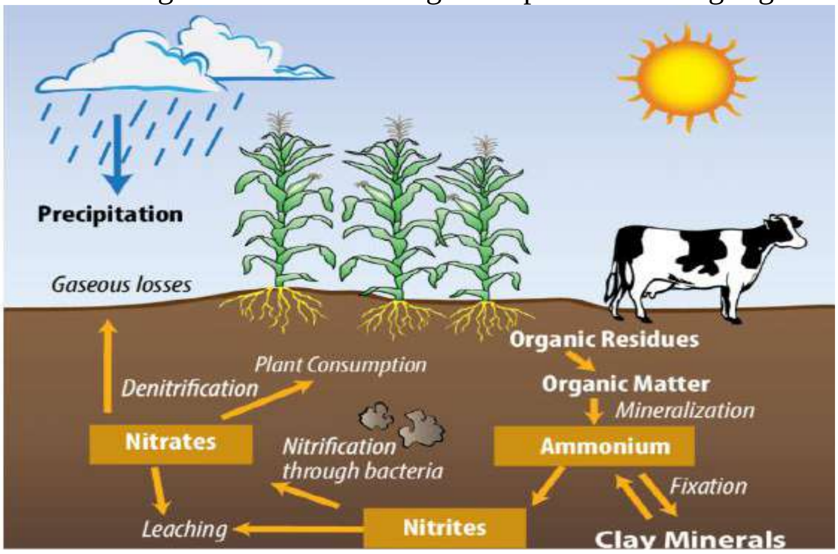

Figure 1 : Nitrogen Cycle

FACTORS INFLUENCING NITROGEN CYCLING IN INDIA

Nitrogen cycling in India, as in other parts of the world, is influenced by a variety of factors. Some of these factors include:

Climate: Climate has a significant impact on nitrogen cycling, as temperature and precipitation can affect the rates of nitrogen fixation, nitrification, denitrification, and ammonia volatilization.

Agriculture: The use of synthetic fertilizers and the cultivation of nitrogen-fixing crops can greatly influence the nitrogen cycle in India. Over-application of fertilizers can lead to nitrate leaching and runoff, which can contaminate groundwater and surface waters.

Land Use: The type of land use (e.g., agricultural, urban, forest) can impact the nitrogen cycle. For instance, urban areas may have higher rates of nitrogen deposition due to vehicular emissions, while agricultural areas may have higher rates of fertilizer application.

Soil Type: Different soil types can influence the nitrogen cycle by affecting the rates of nitrogen fixation, nitrification, and denitrification. For example, sandy soils may have higher rates of nitrate leaching, while clay soils may have higher rates of denitrification.

Vegetation: The type of vegetation present can influence the nitrogen cycle by affecting the rates of nitrogen fixation, uptake, and decomposition. For example, legumes are known for their ability to fix atmospheric nitrogen, while certain types of plants are more efficient at taking up nitrogen from the soil.

Microbial Activity: Microbial activity is a key driver of the nitrogen cycle, as microbes are responsible for processes such as nitrogen fixation, nitrification, and denitrification. The abundance and activity of these microbes can be influenced by factors such as soil pH, temperature, and moisture content.

Population Growth and Urbanization: As the population grows and urbanizes, the demand for food increases, leading to more intensive agricultural practices and increased use of nitrogen fertilizers. Urbanization can also lead to increased nitrogen deposition from vehicular and industrial emissions.

Water Management Practices: Irrigation practices can influence nitrogen cycling by affecting soil moisture levels, which in turn can affect microbial activity and nitrogen transformation processes.

Government Policies: Government policies related to fertilizer use, agricultural practices, and environmental protection can also influence nitrogen cycling in India.

NITROGEN MANAGEMENT PRACTICES IN INDIAN AGRICULTURE

Fertilizer Application Methods:

a) Broadcasting: Broadcasting is the most common method of fertilizer application in India, especially in small and marginal farms. The fertilizer is uniformly distributed across the field, either by hand or using a mechanical spreader. The advantages of broadcasting are its simplicity and speed. However, the drawbacks include potential uneven distribution and higher nitrogen losses. Uneven distribution can lead to some areas receiving too much fertilizer, while others receive too little. This can affect crop growth and yield. Additionally, nitrogen losses can occur through volatilization (the conversion of ammonium to ammonia gas, which is then lost to the atmosphere) and leaching (the downward movement of nitrate through the soil, potentially contaminating groundwater).

b) Side-dressing: Side-dressing is a method where the fertilizer is placed in bands to one side of the plant row, either on the surface or a few inches below. This method is more targeted compared to broadcasting, as the fertilizer is placed closer to the plant roots. This can result in more efficient nutrient uptake by the plants. However, side-dressing is more labor-intensive and can be challenging to implement in large fields.

c) Drip Irrigation: Drip irrigation involves the slow delivery of water to plants using a network of pipes, valves, tubing, and emitters. In the context of nitrogen management, fertilizers can be dissolved in the irrigation water and delivered directly to the plant root zone. This method, known as fertigation, is highly efficient as it reduces nutrient losses and ensures that nutrients are available where and when the plants need them. However, the initial setup costs for a drip irrigation system can be high.

d) Foliar Application:

Foliar application involves spraying liquid fertilizer directly onto plant leaves. This method allows for rapid absorption of nutrients through the leaf surface. It is particularly useful for addressing micronutrient deficiencies. However, foliar application is generally less effective for macronutrients like nitrogen, as plants take up most of their nitrogen through their roots.

2. Timing:

a) Pre-planting:

In pre-planting application, nitrogen fertilizers are applied to the soil before planting the crop. This provides an initial boost of nutrients that can promote early growth and establishment. However, the risk with pre-planting application is that if there is a significant delay between application and planting, nitrogen can be lost through leaching or volatilization.

b) At planting:

In at-planting application, nitrogen fertilizers are applied at the same time the crop is planted. This method is more targeted and reduces the risk of nitrogen losses compared to pre-planting application. It ensures that the nitrogen is available in the soil when the crop begins to grow and establish roots.

c) Split application:

Split application involves dividing the total nitrogen fertilizer into multiple doses and applying them at different growth stages of the crop. This method is designed to match the plant's nitrogen uptake more closely and reduce overall nitrogen losses. By applying nitrogen in smaller amounts and more frequently, there is less risk of leaching and volatilization. Additionally, split application can be more responsive to changing weather conditions and soil moisture levels.

3. Rates:

Determining the right amount of nitrogen to apply is a complex process that depends on various factors. These include the type of crop, soil type, weather conditions, and the desired yield. Over-application of nitrogen can lead to environmental issues such as nitrate leaching into groundwater and emissions of nitrous oxide, a potent greenhouse gas. Therefore, determining the right amount of nitrogen is crucial for sustainable agriculture.

One approach to determining the right nitrogen rate is soil testing. By analyzing the nutrient content of the soil, farmers can determine how much additional nitrogen is needed to meet the crop's requirements. Additionally, the use of decision support tools and models can help farmers make more informed decisions about nitrogen application rates. In conclusion, efficient nitrogen management in Indian agriculture involves the careful selection of fertilizer application methods, timing, and rates. Integrating practices such as precision farming, soil testing, and the use of slow-release fertilizers can further enhance nitrogen use efficiency and reduce environmental impacts.

Role of Integrated Nutrient Management and precision Agriculture in Optimizing Nitrogen

Integrated Nutrient Management (INM): INM is an approach that aims to increase agricultural productivity while minimizing environmental impacts. It involves the judicious use of chemical fertilizers, organic manures, green manures, and biofertilizers to meet the nutrient requirements of crops. INM considers the nutrient contributions from different sources and synchronizes them with crop needs. Here's how INM can help optimize nitrogen use:

a) Source Optimization: INM encourages the use of diverse nutrient sources, which can reduce the dependence on synthetic nitrogen fertilizers. For instance, using biofertilizers like Rhizobium or Azotobacter can fix atmospheric nitrogen in the soil. Similarly, applying organic manures like compost or vermicompost can provide slow-release nitrogen.

b) Timing and Application Methods: INM emphasizes matching nutrient application with crop growth stages. It encourages split application of nitrogen to synchronize with the crop's uptake pattern. This approach reduces nitrogen losses through leaching or volatilization.

c) Soil Health Enhancement: INM practices like green manuring and crop rotation help maintain and improve soil health. Healthy soils can better retain nutrients, reducing nutrient runoff and leaching. This, in turn, optimizes nitrogen use efficiency.

Precision Agriculture (PA): PA, also known as smart farming, uses technology to manage farm resources more efficiently. It involves the use of sensors, GPS, remote sensing, and data analytics to monitor and manage crop growth. Here's how PA can help optimize nitrogen use:

a) Variable Rate Application: PA technologies like GPS-guided variable rate application systems can apply different rates of nitrogen fertilizer to different parts of the field based on the crop's needs. This ensures that each area of the field gets the right amount of nitrogen, reducing over-application and optimizing nitrogen use.

b) Soil and Plant Monitoring: PA uses sensors to monitor soil properties like moisture, pH, and nutrient levels. By monitoring the soil's nitrogen levels in real-time, farmers can apply the right amount of nitrogen when and where it's needed, reducing losses and improving efficiency.

c) Data-Driven Decision Making: PA generates a large amount of data, which can be analyzed to provide insights into crop health, growth patterns, and nutrient requirements. This data-driven approach enables more informed decision-making regarding nitrogen application.

d) Remote Sensing and Imaging: PA technologies like drones and satellites can provide high-resolution images of fields. These images can be analyzed to assess crop health, identify nutrient deficiencies, and guide targeted nitrogen application. By combining the principles of INM with the technologies of PA, farmers can optimize nitrogen use in agriculture. This not only improves crop productivity and quality but also minimizes environmental impacts, making agriculture more sustainable and resilient.

ENVIRONMENTAL IMPLICATIONS OF NITROGEN CYCLING IN INDIA

Air Pollution: The conversion of ammonia-based fertilizers into nitrous oxide and nitrogen oxides in the soil can lead to the emission of these pollutants into the atmosphere. Nitrogen oxides contribute to the formation of ground-level ozone, which is a major component of smog. Smog can cause respiratory problems, reduce lung function, and exacerbate asthma. Nitrogen oxides can also react with water vapor in the atmosphere to form nitric acid, which contributes to acid rain. Acid rain can damage vegetation, acidify soil and water bodies, and corrode buildings and infrastructure.

Water Pollution: The runoff of nitrogen from agricultural fields, urban areas, and wastewater treatment plants can lead to the contamination of rivers, lakes, and groundwater. Nitrogen in the form of nitrate is a common contaminant in drinking water sources. High nitrate levels in drinking water can pose a serious health risk, particularly for infants. The contamination of water bodies with nitrogen can also lead to algal blooms, which produce toxins that can harm aquatic organisms and pose a risk to human health.

Climate Change: Nitrous oxide is a potent greenhouse gas that is emitted from agricultural soils, livestock manure, and combustion processes. It has a global warming potential that is approximately 300 times greater than carbon dioxide over a 100-year period. The increasing use of nitrogen-based fertilizers in India contributes to the release of nitrous oxide into the atmosphere, which in turn contributes to global warming and climate change.

Soil Degradation: The excessive application of nitrogen fertilizers can lead to the accumulation of nitrate in the soil, which can have negative effects on soil health. High nitrate levels can disrupt the balance of soil nutrients and affect the activity of soil microorganisms. This can reduce soil fertility and make the soil more susceptible to erosion.

Biodiversity Loss: Changes in nitrogen cycling can have cascading effects on ecosystems and lead to a loss of biodiversity. Excessive nitrogen deposition can favor the growth of certain plant species over others, leading to a reduction in plant diversity. This can have negative effects on other organisms in the ecosystem, including insects, birds, and mammals.

Transboundary Pollution: Nitrogen pollution can have transboundary implications, as airborne nitrogen compounds can travel long distances before being deposited. This can lead to the contamination of air and water quality in neighboring countries, which can have negative effects on ecosystems and human health.

Human Health: Apart from methemoglobinemia, long-term exposure to nitrate-contaminated drinking water has also been linked to an increased risk of certain types of cancer, including stomach, esophageal, and bladder cancer.

Regional Variability in Nitrogen Use: India's vast and diverse geography means that the patterns of nitrogen use can vary significantly from one region to another. In regions where high-intensity agriculture is practiced, such as Punjab and Haryana, the environmental implications of nitrogen cycling can be more severe. The high levels of nitrogen fertilizer use in these regions can result in higher emissions of nitrogen oxides and nitrous oxide, greater runoff of nitrogen into water bodies, and more significant impacts on soil health.
Shifts in Aquatic Ecosystems: The introduction of excess nitrogen into aquatic ecosystems through runoff can shift the balance of species in these systems. For instance, nitrogen-rich conditions can promote the growth of cyanobacteria, which can outcompete other phytoplankton species and lead to harmful algal blooms. These blooms can produce toxins that are harmful to fish and other aquatic organisms, as well as to humans who consume contaminated water or seafood.
Soil Acidification: The excessive use of nitrogen fertilizers can lead to soil acidification. Soil acidification can have detrimental effects on plant growth, soil structure, and the availability of nutrients. It can also negatively affect soil microbial communities, leading to a decline in soil biodiversity.
Groundwater Contamination: In addition to surface water contamination, excessive nitrogen application can lead to the leaching of nitrates into groundwater. Groundwater is a major source of drinking water in many parts of India, and nitrate contamination of groundwater can pose a significant risk to human health.
Air Quality and Human Health: The contribution of nitrogen oxides to air pollution can have serious implications for human health. Apart from respiratory issues, long-term exposure to elevated levels of nitrogen oxides can lead to cardiovascular diseases and other health problems. Moreover, the formation of particulate matter (PM2.5) from nitrogen oxides can also lead to respiratory and cardiovascular issues.
Greenhouse Gas Emissions from Livestock: Livestock production is another significant source of nitrogen emissions in India. Ruminant animals, such as cattle and buffalo, produce methane (a potent greenhouse gas) as a byproduct of digestion. Manure management practices can also result in the emission of nitrous oxide. These greenhouse gases contribute to global warming and climate change.
Impact on Cultural Practices: In some parts of India, traditional agricultural practices that have been sustainable for centuries are being replaced by high-input, intensive farming practices that rely heavily on nitrogen fertilizers. This shift can have profound impacts on cultural practices and ways of life, as well as on the long-term sustainability of agriculture in these regions.
Policy and Regulation: There is a need for stronger policies and regulations to manage nitrogen use in India. This includes better enforcement of existing regulations, as well as the development of new policies that promote sustainable nitrogen management practices.
Public Awareness and Education: Raising public awareness about the environmental implications of nitrogen cycling and the importance of sustainable nitrogen management practices is critical. Public education campaigns can help to inform citizens about the impacts of nitrogen pollution on air and water quality, human health, and biodiversity. This can help to build public support for policies and practices that promote sustainable nitrogen management.

Strategies for Mitigating Impacts through Sustainable Nitrogen Management

Mitigating the impacts of nitrogen pollution necessitates a comprehensive approach that takes into account the entire nitrogen cycle. Sustainable nitrogen management is pivotal in addressing the environmental and health consequences of excessive nitrogen use, especially in agriculture. To optimize nitrogen use in agriculture, farmers can employ precision farming techniques, leveraging technologies such as variable rate technology (VRT) and remote sensing. These technologies enable farmers to apply nitrogen fertilizers judiciously, minimizing wastage and environmental contamination. Additionally, promoting the use of cover crops can capture surplus nitrogen in the soil, preventing it from leaching into water bodies or being released into the atmosphere. Cover crops also enrich the soil, fostering improved agricultural productivity. Another important strategy is to enhance the efficiency of nitrogen fixation in crops. Developing crop varieties that can more effectively fix nitrogen from the atmosphere can diminish the reliance on synthetic nitrogen fertilizers. This can be complemented by implementing integrated pest management (IPM) practices, which offer holistic pest control solutions that reduce the need for pesticides and, consequently, the nitrogen load in the environment. Moreover, improving wastewater treatment infrastructure to eliminate more nitrogen from effluents is critical. This prevents the release of nitrogen into water bodies, mitigating eutrophication and preserving aquatic ecosystems. Sustainable livestock management practices, including optimizing feed to minimize nitrogen excretion and ensuring proper manure management, also contribute to reducing nitrogen pollution. Promoting nitrogen recycling technologies that capture and reuse nitrogen from waste streams can further decrease the demand for synthetic fertilizers. Public awareness and education are essential to drive behavioral change among farmers, policymakers, and consumers. Informed stakeholders are more likely to adopt sustainable nitrogen management practices, contributing to pollution mitigation efforts. Government policies and regulations also play a significant role in shaping sustainable nitrogen management. Regulations that limit nitrogen emissions, subsidies for environmentally friendly farming practices, and incentives for adopting best management practices can incentivize stakeholders to prioritize sustainable nitrogen management. Lastly, continuous research and innovation in nitrogen management practices, alternative fertilizers, and crop genetics are crucial for developing new technologies and strategies that enhance the sustainability of nitrogen use in agriculture.

Table 1. Estimate of N containing GHG from agro-ecosystem of India

N form	Source	Amount Tg N	Estimation year	Reference
N_2O	All agricultural activities	0.24	1990	25
	Fertilizer use	0.012	1989–90	26, 27
		0.16	1995	
	Burning of residues	0.011	1990	27, 28
		0.03	1995	
	Biological N fixation	0.01	1995	27
	Livestock	0.01	1995	27
NO_x ($NO + NO_2$)	Biomass burning	0.1	1990	25, 29
		0.6	1995	

Crop rotation is a practice where different crops are grown in a sequence on the same piece of land over multiple growing seasons. This can help to improve soil health, reduce soil erosion, and break pest and disease cycles. Rotating crops with legumes, which are plants that can fix nitrogen from the air, can also increase nitrogen availability in the soil and reduce the need for synthetic nitrogen fertilizers. Using biofertilizers and organic fertilizers, which are derived from plant and animal materials, can help to improve soil health and fertility. These fertilizers often release nitrogen slowly over time, which can help to minimize nitrogen losses and reduce the risk of pollution. Establishing buffer strips and wetlands along water bodies can help to capture and filter out excess nitrogen from agricultural runoff before it reaches water bodies.

Table 2. Effect of green revolution and industrialization on Nr creation and GHG emission (Tg N) from India

N pool	1950–51 level	1995–96 level	Magnitude of Nr added/difference
N fertilizer	0.06	10.8	10.74
BNF	0.55	1.14–1.18	0.59–0.63
Crop production	2.94	12.47	9.53
Livestock	0.97	1.62	0.65
Land-use change (mha)@			
Net sown area	118	141	23
Gross cropped area	132	188	56
Organic N (as % of total N)*	65–95	55–94	–
GHG production			
N_2O	–	0.26	–
NO_x	–	3.46	–
NH_3	–	7.4	–

*Values are in the range across various regions of India (Srivastava and Singh[36]). @This accelerates N mineralization and increased N fertilizer use.[3]

These natural filters can reduce the risk of nitrogen pollution in surface and ground waters. Implementing precision irrigation systems, such as drip irrigation, can help to minimize water use and reduce the risk of nitrogen leaching into groundwater. Proper irrigation management can also improve crop yields and water use efficiency. Proper management of animal manure, including composting and anaerobic digestion, can help to reduce nitrogen emissions and recycle nutrients back into the soil. This can also help to reduce the demand for synthetic nitrogen fertilizers and improve soil health. Governments can implement regulations and certification programs to encourage sustainable nitrogen management practices. For example, nutrient management plans can be required for farms to ensure that they are using nitrogen fertilizers efficiently and minimizing environmental impacts. Certification programs, such as organic farming certifications, can also incentivize sustainable practices and provide market access for sustainably produced products. Collaboration between farmers, researchers, policymakers, and other stakeholders can help to develop and implement sustainable nitrogen management practices. Knowledge sharing, capacity building, and the development of best practices can help to accelerate the adoption of sustainable practices and reduce nitrogen pollution.

Research Priorities

Bringing down the guesswork on N pools and fluxes

Studies assessing diverse N pools, N-cycling, and N mass balances at all spatial and temporal scales are plagued by significant variability and uncertainty. Variability in the measurements is introduced on several fronts, including data sources, models/methods utilized, changes in cropping pattern, biomass burning, environmental and climatic conditions. It is important to determine appropriate emission coefficients by measuring across multiple seasons in India's varied cropping systems, as N_2O emission from soils is a major source of N containing GHG emission from the country. Inputs and losses must therefore be portrayed as ranges rather than single numbers if we are to gain a comprehensive understanding of the myriad N fluxes and the large variability among them.

Energy and food production

In India, the production of Nr. 6 is expected to rise as the country's rapidly expanding population necessitates more food and energy to keep the economy growing. Reducing the pace of inorganic N addition, expanding the adoption of organic agricultural practices, and enacting the necessary policy direction are all promising avenues for reducing N emissions from agroecosystems. N management techniques that optimize output while minimizing N losses in agroecosystems can be considerably improved through the creation of databases on plant residues, their composition, and N release patterns on the one hand, and daily/weekly crop N requirements on the other. Not only should animal waste be collected and used effectively, but the organic waste/manure resources themselves also need to be brought up to date in terms of their quantity, quality, and use pattern. Precision farming technology adapted to the Indian agro-ecosystem can benefit from RS and GIS inputs, leading to increased NUE.

Variability in Emissions' locations and times of Release

The rates at which land and water systems denitrify fixed N to N_2 are crucial to human influences on the N cycle. Denitrification rates in both controlled and uncontrolled terrestrial and aquatic ecosystems are poorly understood. This is the primary barrier preventing precise modeling of the N cycle. Ammonia volatilization is also highly influenced by seasonal changes in India's weather (air and soil temperature, precipitation, wind, and RH). By running model simulations in tandem with large-scale observations and connecting point measurements to geographical datasets (through, say, sensors on aircraft or satellites), precise estimations can be obtained.

Digital Soil datasets

The global N budget may be significantly impacted by the soil's 'background' emissions, which occur at low rates but cover a large region. The importance of linking emission models to anticipate both background and treatment emission values necessitates the creation of national digital soil information at higher resolution. To better quantify N_2O, more studies collecting data from terrestrial and aquatic systems, especially long-term measurements, are needed.

Atmospheric deposition

The US Environmental Protection Agency's Clean Air Status and Trends Network (CASTNet) employs the inferential approach70 to estimate dry deposition. For duplicate meteorological and concentration observations gathered from five CASTNet sites, the annual average precision statistics were also generated. This highlights the importance of establishing a system of dry deposition measurement sites across India for verifying the accuracy of any dry deposition models. Additionally, models should be created and tested to investigate the relationship between seasonal changes in surface cover (snow cover, vegetation, and micro-meteorology) and the wet and dry deposition fluxes and velocities.

Attend to the Cyclic Conjunctions

Stoichiometric correlations between carbon and nitrogen establish a connection between the two cycles. Therefore, the linked process71 needs to be taken into account by diagnostic and prediction models. These two material balance cycles, particularly the N cycle over India, should be at the center of biogeochemical cycle research aimed at assessing the effects of human land-use changes on natural ecosystems.

Process-based model-linked RS

In place of emission factors, process-based models should be examined. Incorporating the effects of environmental parameters on NH_3 production/deposition, the process-oriented models of soil NH_3 emission could be used as a foundation for future NH_3 inventory studies. Process-based soil N emission models, such as the CASA model, CENTURY/DAYCENT, and DNDC, provide a potential way to examine the impact of anticipated future climate, and land-use and land-cover variables on soil-biogenic NO_x emissions. The process models can also be used to isolate the factors that have the greatest impact on the soil's biogenic NO_x emissions.

To estimate the impact of microclimate change on different N pools and predict future changes, regional climatic models can be used with inputs from satellite-derived weather parameters and ground observations in the GIS database that are linked to the nitrogen cycle at the regional scale. Extensive observations, GIS databases characterizing animal manure and other main sources of NH3 emissions, and the development and use of process-based models are required for an accurate estimate. The Global Atmosphere Integrity Monitoring (GAIM) project is part of the ICSU's International Geosphere Biosphere Program (IGBP). Modeling the N cycle will help us better understand how to control Nr in the biosphere and protect against the negative impacts of reactive nitrogen on water, air, and human health. To back up the Government's fertilizer pricing strategy, a robust research database on N use, hot- spot areas of N pollution, and the socio-economic conditions of farmers in different agro-ecosystems of India is necessary. The usage of nitrogen fertilizer in Indian agriculture will be greatly aided by this.

FUTURE DIRECTIONS FOR RESEARCH AND POLICY

- Investigate the ethical and social implications of emerging technologies such as artificial intelligence, biotechnology, and nanotechnology.
- Develop strategies for mitigating climate change and adapting to its impacts.
- Explore new approaches for addressing global health challenges, including pandemics, chronic diseases, and health disparities.
- Investigate the impact of digital learning and remote education on student outcomes, and develop policies to ensure equitable access to quality education.
- Research the causes and consequences of economic inequality, and identify policies to promote economic opportunity and social mobility.
- Develop strategies to protect against cyber threats and ensure the security of digital infrastructure.
- Investigate the impacts of social media, work stress, and other factors on mental health, and develop policies to promote mental health and well-being.
- Research the implications of an aging population on healthcare, social security, and the workforce, and develop policies to support the needs of older adults.

CONCLUSION

Soil nitrogen cycling is a critical aspect of nutrient management that has profound implications for agricultural productivity and environmental sustainability in India. Through a nuanced understanding of the processes involved, including mineralization, nitrification, denitrification, volatilization, and immobilization, we can develop strategies to optimize nitrogen use in agriculture. This not only ensures higher crop yields but also minimizes the environmental impacts associated with nitrogen cycling, such as water pollution, greenhouse gas emissions, and biodiversity loss. The challenge of managing soil nitrogen cycling in India is compounded by diverse agro-ecological zones, climate variability, and diverse cropping systems. As such, region-specific and crop-specific nitrogen management practices are essential. The integration of traditional and modern agricultural practices, along with the adoption of precision agriculture technologies, can further enhance the efficiency of nitrogen use. To achieve sustainable nitrogen management, it is crucial to foster collaborative research efforts that focus on the interactions between climate change, nitrogen cycling, and agricultural productivity. Policy initiatives should promote the adoption of sustainable nitrogen management practices, incentivizing farmers to implement best management practices that are aligned with the principles of environmental conservation.

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