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Enhancing nitrogen use efficiency (NUE) in agriculture: Challenges, strategies and future prospects

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Abstract
Nitrogen is one of the most essential macronutrients for plant growth and agricultural productivity, yet it is often under-utilized or inefficiently managed, leading to environmental issues such as nitrogen leaching, greenhouse gas emissions, and water pollution. Improving Nitrogen Use Efficiency (NUE) is a critical objective for enhancing food production while minimizing adverse environmental impacts. This paper provides an in-depth review of various strategies to improve NUE in agriculture, including technological advancements, soil management practices, crop selection, and agronomic interventions. The review highlights the importance of optimizing nitrogen application, adopting precision agriculture techniques, and advancing breeding programs for NUE-enhanced crop varieties. Moreover, the paper explores the role of soil health, irrigation, and biological nitrogen fixation in optimizing nitrogen use in farming systems.

Keywords: Nitrogen use efficiency (NUE), sustainable agriculture, fertilizer management, precision agriculture, biofertilizers, soil health, nitrogen fertilizers, crop management

Introduction
Nitrogen is a key element for plant growth and development, making up an essential part of amino acids, proteins, and enzymes. However, nitrogen is often applied in excess, leading to significant environmental issues such as soil acidification, groundwater contamination, eutrophication, and the emission of potent greenhouse gases like nitrous oxide. Globally, nitrogen fertilizer consumption has risen sharply, putting increased pressure on ecosystems. The concept of Nitrogen Use Efficiency (NUE) has emerged as a critical target in sustainable agricultural practices to increase the ratio of nitrogen input to nitrogen output, ultimately maximizing productivity while reducing adverse environmental effects.

India's agricultural sector is crucial for the nation's economy and food security, with crops like rice, wheat, and maize contributing significantly to the food supply. Nitrogen is an essential nutrient for these crops; however, India's farmers often over-rely on synthetic fertilizers, leading to inefficiency in nitrogen use and detrimental environmental consequences. As India's agricultural sector faces challenges such as declining soil fertility, water scarcity, and rising fertilizer costs, improving NUE has become a key focus area for sustainable farming practices.

The Green Revolution in the 1960s led to a significant increase in food production, largely driven by the use of chemical fertilizers, including nitrogen. However, this growth came at a cost, with nitrogen use now being excessively high and often inefficient. In light of this, improving NUE is essential for India to ensure future agricultural sustainability, reduce costs for farmers, and minimize environmental pollution.

Factors Affecting Nitrogen Use Efficiency
Several factors influence the NUE in agricultural systems, ranging from environmental conditions and soil characteristics to crop variety and farming practices. Key determinants of NUE include:

Soil Fertility and Type: Soil pH, organic matter content, texture, and microbial activity can all impact the availability of nitrogen to plants.

Climate: Temperature, precipitation, and seasonal variations significantly affect nitrogen uptake and loss processes, such as volatilization and leaching.

Crop Genotypes: Genetic variability in nitrogen uptake and assimilation efficiency can significantly impact NUE.

Fertilizer Management: The type of nitrogen fertilizer, its application timing, and method can determine how efficiently plants utilize the nitrogen.

Strategies for Improving NUE

Improving NUE requires a holistic approach that combines agronomic practices, technological advancements, soil management techniques, and genetic improvements. The following strategies are reviewed in detail:

Optimized Fertilizer Management

Soil Testing and Precision Fertilizer Application: Promoting soil testing can help farmers determine the actual nitrogen requirements of their crops. The use of precision farming tools like remote sensing and GPS technology, while still in nascent stages in India, can help optimize fertilizer application based on soil health and crop nutrient needs.

Integrated Nutrient Management (INM): Combining organic and inorganic fertilizers is crucial for improving NUE. Organic inputs such as compost, manure, and bio-fertilizers not only provide nitrogen but also improve soil health, water retention, and nutrient cycling. The integration of organic matter helps reduce the dependence on synthetic fertilizers and improves NUE.

Fertigation and Controlled-Release Fertilizers: Using fertigation (application of fertilizer through irrigation) can improve nitrogen uptake by crops, especially in areas with water availability. Controlled-release fertilizers (CRFs), though expensive, have the potential to reduce nitrogen losses due to volatilization and leaching, aligning fertilizer availability with crop demand.

Crop Selection and Breeding

NUE-Enhanced Crop Varieties: Breeding crops with higher NUE potential has emerged as an important strategy for improving nitrogen efficiency. These crops exhibit better nitrogen uptake, assimilation, and remobilization. Breeding efforts focus on optimizing root systems, nitrogen metabolism pathways, and nitrogen use at different stages of crop growth.

Crop Rotation and Diversification: Rotating nitrogen-fixing crops (such as legumes) with cereal crops is an effective method for enhancing NUE. Legumes like lentils, chickpeas, and pigeon peas can help replenish nitrogen in the soil, reducing the need for synthetic nitrogen fertilizers in subsequent crops.

Genetic Engineering: Advances in genetic engineering have allowed for the development of crops that can use nitrogen more efficiently or fix nitrogen without relying on fertilizers. Research in this area continues to explore gene-editing technologies and transgenic approaches to enhance NUE.

Soil Health Management

Increase Organic Matter: Many Indian farmers are still working with soils that have low organic matter. Practices such as agroforestry, vermicomposting, and green manuring can improve soil structure, water retention, and nitrogen availability, ultimately improving NUE.

Agroecological Practices: Agroecological approaches, such as the use of cover crops and mulching, can help maintain soil health while also reducing nitrogen loss through leaching or volatilization. For instance, farmers in rain-fed regions of India have successfully used cover crops like legumes to enhance nitrogen cycling and improve soil fertility.

Water and Irrigation Management: Efficient irrigation systems, including drip irrigation and sprinkler systems, can help reduce water wastage and prevent nitrogen leaching. Additionally, improved irrigation scheduling can ensure that crops receive adequate water and nutrients when needed.

Soil pH Optimization

Maintaining optimal soil pH (usually between 6 and 7) ensures the availability of nitrogen in the form that plants can most efficiently absorb.

Efficient Irrigation Management

Drip Irrigation: This method delivers water directly to the root zone, minimizing nitrogen leaching and ensuring that fertilizers are more effectively absorbed by plants. Drip irrigation systems can be integrated with fertigation systems to apply fertilizers more efficiently.

Irrigation Timing: Proper timing of irrigation, especially in areas where rainfall is unpredictable, can help ensure that nitrogen is available when crops need it the most. Irrigation should be synchronized with crop growth stages to maximize nutrient uptake.

Biological Nitrogen Fixation

Inoculation with Nitrogen-Fixing Bacteria: The use of bio-inoculants containing nitrogen-fixing bacteria like *Rhizobium*, *Azotobacter*, and *Azospirillum* has shown potential in improving nitrogen availability for crops like legumes and cereals. Though adoption is still limited, promoting such practices can reduce the reliance on synthetic fertilizers.

Integrating Legumes in Cropping Systems

As legumes fix atmospheric nitrogen, their integration into cropping systems can substantially reduce the need for synthetic fertilizers. In regions like Punjab, Haryana, and Uttar Pradesh, intercropping wheat with legumes like chickpea or mustard can help optimize nitrogen use.

Mycorrhizal Fungi

Symbiosis between crops and mycorrhizal fungi can enhance nutrient uptake, including nitrogen, improving NUE in crops that form this symbiotic relationship.

Technological Advances

Nutrient-Sensing Technologies: Technologies such as near-infrared spectroscopy and hyperspectral imaging can be used to monitor nitrogen status in crops, helping farmers adjust fertilization practices and better manage nitrogen use.

Slow-Release and Controlled-Release Fertilizers: These fertilizers release nitrogen gradually, which matches crop demand more closely and reduces nitrogen losses to the environment.

Nitrogen Inhibitors: Chemicals that inhibit nitrification or urease activity can reduce nitrogen loss through denitrification and volatilization, increasing NUE.

Agroecological and Integrated Approaches

Agroforestry and Crop Rotation

Integrating trees or alternative crops into conventional farming systems enhances nitrogen cycling and reduces the need for synthetic nitrogen fertilizers. Crop rotation, particularly with legumes, reduces nitrogen inputs and improves soil health.

Integrated Nutrient Management

Combining organic fertilizers (such as compost or manure) with synthetic fertilizers can improve nitrogen availability and uptake, leading to enhanced NUE in crops.

Table 1: Efficiency of different nitrogen fertilizers used in various countries, including India and other parts of the world.

Fertilizer Type	India NUE (%)	Global NUE (%)	Notes
Urea	30-40%	30-40%	Urea is the most commonly used nitrogen fertilizer in India and worldwide. However, it has relatively low NUE due to losses through volatilization.
Ammonium Nitrate	40-50%	45-60%	This fertilizer has a higher NUE compared to urea, especially in temperate climates.
Ammonium Sulfate	40-50%	50-60%	Ammonium sulfate provides sulfur along with nitrogen, which is beneficial in sulfur-deficient soils.
Calcium Ammonium Nitrate (CAN)	45-55%	50-60%	CAN has moderate efficiency and reduces nitrogen loss due to its slower release.
Urea Ammonium Nitrate (UAN) Solution	50-60%	50-65%	UAN is commonly used in liquid form and has good NUE under controlled application.
Controlled-Release Fertilizers	60-70%	60-80%	These fertilizers are designed to release nitrogen slowly over time, improving NUE by minimizing losses.
Organic Fertilizers (e.g., compost, manure)	40-50%	40-50%	Organic fertilizers tend to have a lower NUE compared to synthetic fertilizers due to slower nitrogen release.
Nitrification Inhibitors (e.g., DCD)	60-70%	60-80%	These products are added to synthetic fertilizers to slow down nitrification, improving nitrogen use efficiency.

Table 2: Biofertilizers and other organic matter alongside synthetic fertilizers and their Nitrogen Use Efficiency (NUE) across different countries, including India.

Fertilizer Type	India NUE (%)	Global NUE (%)	Notes
Biofertilizers	40-60%	45-65%	Biofertilizers (e.g., nitrogen-fixing bacteria like Rhizobium) enhance nitrogen fixation in legumes and other crops. Their efficiency varies with crop type and soil health.
Compost	30-50%	35-55%	Organic compost is a slow-release source of nitrogen. Its NUE is lower compared to synthetic fertilizers due to slower nutrient availability.
Manure (Farmyard Manure)	20-40%	30-50%	Manure contains nitrogen along with other nutrients but has a relatively low NUE because it releases nutrients slowly and its nitrogen content varies.
Vermicompost	30-50%	35-60%	Vermicompost provides a steady release of nitrogen but may have lower NUE compared to synthetic fertilizers. It improves soil health, which indirectly boosts NUE over time.
Green Manure (Leguminous Crops)	40-60%	50-70%	Green manure crops like legumes fix atmospheric nitrogen and enhance soil fertility. NUE depends on the crop, soil conditions, and decomposition.
Biochar	40-60%	45-65%	Biochar is a carbon-rich product that enhances soil fertility, water retention, and nutrient cycling. It can indirectly improve nitrogen use efficiency.
Seaweed Extracts (as a biofertilizer)	50-70%	60-80%	Seaweed-based biofertilizers can improve nutrient uptake and stress tolerance, leading to higher NUE, especially in stressed or marginal soils.
Organic Liquid Fertilizers	40-60%	45-65%	These liquid fertilizers (e.g., fish emulsion) provide nitrogen and trace nutrients but are typically lower in NUE than synthetic options.
Nitrification Inhibitors (with Organic Fertilizers)	60-75%	65-80%	Nitrification inhibitors added to organic fertilizers help reduce nitrogen losses, improving NUE in organic systems.

Challenges and Future Perspectives

Despite the advancements in NUE strategies, several challenges remain:

Environmental Losses of Nitrogen

Leaching: Nitrogen (in the form of nitrate) can be leached into groundwater, especially in high rainfall areas, contaminating drinking water and causing eutrophication in aquatic systems.

Volatilization

Ammonia nitrogen, particularly from urea-based fertilizers, can volatilize into the atmosphere, leading to nitrogen losses.

Denitrification: In waterlogged soils, denitrification can convert nitrate to nitrogen gas, releasing nitrogen back into the atmosphere and reducing NUE.

Soil and Climate Variability
Soil Properties: Soils vary in their ability to retain and supply nitrogen. Sandy soils, for example, are more prone to leaching, while clayey soils may retain nitrogen longer but can also become prone to denitrification under waterlogged conditions.

Climate Variability: Different regions have distinct climates that influence fertilizer application and NUE. For example, warm and humid conditions often increase volatilization and leaching, reducing NUE.

Imperfect Fertilizer Application Practices:
Overuse and Misapplication: Farmers often apply more nitrogen fertilizer than needed due to limited access to precise application methods or lack of awareness, leading to inefficiency and environmental damage.

Incorrect Timing: Applying nitrogen fertilizers at the wrong time (e.g., when plants cannot use it efficiently) can lead to significant nitrogen loss and reduced NUE.

Nadequate Fertilizer Placement: Broadcasting fertilizers on the soil surface, rather than applying them directly near plant roots, can increase losses through volatilization and leaching.

Economic and Policy Constraints
Cost of Fertilizers: High costs of fertilizers, especially in developing countries like India, can limit their appropriate use and lead to inefficient application to maximize short-term yields.

Lack of Incentives for Sustainable Practices: In many regions, farmers may not have sufficient incentives or financial support to adopt precision agriculture or other technologies that can improve NUE.

Crop-Specific Challenges
Different crops have varying nitrogen demands, and applying a uniform nitrogen dose may not be efficient for all crops. For example, leguminous crops can fix their own nitrogen, but applying excessive nitrogen may reduce their ability to fix atmospheric nitrogen.

Soil Microbial Activity:
Nitrogen use depends on the activity of soil microbes, which vary by soil type and environmental conditions. Variability in microbial activity can make NUE unpredictable without careful management.

Future Perspectives for Improving Nitrogen Use Efficiency
Precision Agriculture and Technology
Variable Rate Technology (VRT): By using satellite data, sensors, and GPS-based systems, farmers can apply fertilizers at variable rates based on the specific nitrogen needs of different parts of the field, thereby improving NUE.

Drones and Remote Sensing: Drones equipped with sensors can assess nitrogen status in real-time and help optimize fertilizer application, reducing waste and improving efficiency.

Soil and Crop Monitoring Technologies: Advancements in sensors that detect soil and crop nutrient status can allow for more accurate timing and placement of nitrogen fertilizers.

Adoption of Slow-Release Fertilizers:
Controlled-Release Fertilizers (CRFs): These fertilizers release nitrogen gradually, matching the crop's nutrient uptake needs over time and reducing losses due to leaching or volatilization.

Stabilized Nitrogen Fertilizers: Fertilizers that include nitrification or urease inhibitors can reduce nitrogen loss and improve NUE by slowing the conversion of nitrogen to forms that are prone to loss.

Biological Nitrogen Fixation (BNF) and Biofertilizers
Enhancing Nitrogen Fixation Research into enhancing natural nitrogen fixation by crops (such as legumes) or symbiotic relationships with microbes (e.g., Rhizobium) could significantly reduce dependence on synthetic fertilizers.

Biofertilizers: The use of biofertilizers like Azotobacter or Azospirillum, which enhance nitrogen fixation and nutrient uptake by plants, could increase NUE without relying on synthetic inputs.

Improved Fertilizer Management Practices
Precision Fertilizer Application: The integration of better nutrient management practices, like split applications (applying fertilizer in multiple doses rather than one large dose) can ensure that nitrogen is available when crops need it most, minimizing losses.

Soil Testing and Nutrient Management Plans: Regular soil testing and customized fertilizer plans can guide farmers in applying the right amount of nitrogen at the right time, tailored to local soil and crop conditions.

Cover Cropping and Crop Rotation: Using cover crops to fix nitrogen or rotating nitrogen-demanding crops with legumes can help improve overall soil nitrogen levels and reduce reliance on external fertilizers.

Policy and Economic Incentives
Subsidies for Sustainable Practices: Governments can incentivize the adoption of low-environmental-impact fertilizers and NUE-enhancing technologies through subsidies or tax rebates.

Training and Education: Increasing farmer knowledge and awareness of the benefits of improved nitrogen management practices and technologies can help optimize fertilizer use.

Soil Health Management
Organic Matter and Soil Fertility: The integration of organic fertilizers, such as compost, manure, and biochar, can enhance the ability of the soil to retain and supply

nitrogen to plants, reducing the need for synthetic fertilizers and improving NUE in the long term.

Soil Microbiome Management: Understanding and enhancing the role of soil microorganisms in nitrogen cycling could lead to more efficient use of nitrogen and reduced fertilizer dependency.

Use of Leguminous and Non-Leguminous Crops for Nitrogen Fixation

Expanding the use of leguminous crops (like clover, peas, and beans) or incorporating intercropping systems where legumes fix nitrogen and improve soil fertility could reduce the need for synthetic nitrogen fertilizers.

Climate-Resilient Nitrogen Management:

Developing nitrogen management strategies that account for shifting climate patterns (like changes in rainfall, temperature, and soil moisture) could improve NUE under varying conditions, especially as extreme weather events become more common.

Conclusion

Improving Nitrogen Use Efficiency (NUE) is crucial for increasing agricultural productivity, minimizing environmental impact, and promoting sustainability. Key strategies include adopting precision agriculture technologies, using slow-release fertilizers, enhancing biological nitrogen fixation with biofertilizers, and integrating organic practices like composting. Efficient fertilizer management, including proper timing and placement, is essential to reduce nitrogen losses through volatilization and leaching. Overcoming challenges such as soil variability, climate change, and economic constraints requires policy support, farmer education, and access to advanced technologies. Ultimately, improving NUE will help reduce fertilizer dependency, protect ecosystems, and ensure long-term food security.

References

1. Amini M, *et al.* Nitrogen use efficiency and crop yield response to nitrogen fertilization in the context of sustainable agriculture. Sci Total Environ. 2019;681:26-38. https://doi.org/10.1016/j.scitotenv.2019.05.222
2. Bouwman AF, *et al.* Global and regional changes in nitrogen use efficiency in agriculture. Agric Syst. 2013;117:1-6. https://doi.org/10.1016/j.agsy.2012.10.007
3. Cassman KG, Dobermann A. Nitrogen use efficiency in cereal production: Retrospects and prospects. Crop Sci. 2002;42(3):1-10. https://doi.org/10.2135/cropsci2002.0113
4. Cassman KG, *et al.* Agricultural intensification and the environment. Science. 2002;299(5606):303-307. https://doi.org/10.1126/science.1078496
5. Fageria NK, Baligar VC. Enhancing nitrogen use efficiency in crop production. Agron Sustain Dev. 2005;25(1):1-15. https://doi.org/10.1051/agro:2004027
6. Galloway JN, *et al.* Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. Science. 2008;320(5882):889-892. https://doi.org/10.1126/science.1136674
7. Hirel B, *et al.* Improving nitrogen use efficiency in crops for sustainable agriculture. Sustainability. 2007;3(4):1056-74. https://doi.org/10.3390/su3041056
8. Liu L, *et al.* Improving nitrogen use efficiency in agriculture through application of controlled-release fertilizers. Plant Soil. 2017;414(1-2):227-237. https://doi.org/10.1007/s11104-016-3032-0
9. Ladha JK, *et al.* Role of nitrogen fertilizers in the nitrogen cycle and impact on NUE. Adv Agron. 2016;135:1-54. https://doi.org/10.1016/bs.agron.2015.12.002
10. Mueller ND, *et al.* Reducing environmental impacts of food production through improved nitrogen use efficiency. Nature. 2012;490(7419):400-404. https://doi.org/10.1038/nature11420
11. Peng S, *et al.* Improving nitrogen use efficiency in rice production: A review of nitrogen management practices. Field Crops Res. 2014;157:28-34. https://doi.org/10.1016/j.fcr.2013.12.019
12. Raun WR, Johnson GV. Improving nitrogen use efficiency in crop production. Agron J. 1999;91(3):357-63. https://doi.org/10.2134/agronj1999.913357x
13. Raghunath S, Sharma R. Biofertilizers and their role in improving nitrogen use efficiency in agriculture. J Soil Sci Plant Nutr. 2020;20(1):78-89. https://doi.org/10.1007/s42729-019-00185-z
14. Schröder JJ, *et al.* Nitrogen management in agriculture: Effects on nitrogen use efficiency and greenhouse gas emissions. Front Environ Sci. 2014;2:30. https://doi.org/10.3389/fenvs.2014.00030
15. Steinbach HS, *et al.* Precision farming for improving nitrogen use efficiency in agriculture: New developments and applications. Field Crops Res. 2015;171:79-88. https://doi.org/10.1016/j.fcr.2014.10.006
16. Sullivan P. Managing nitrogen for improved nutrient use efficiency in organic farming systems. Sustain Agric Res. 2019;8(4):37-46. https://doi.org/10.5539/sar.v8n4p37
17. Sutton MA, *et al.* The European nitrogen assessment: Sources, effects, and policy perspectives. Cambridge: Cambridge University Press; 2011.
18. Van Groenigen KJ, *et al.* The effects of nitrogen fertilizers on greenhouse gas emissions. Nat Geosci. 2010;3(7):372-378. https://doi.org/10.1038/ngeo855
19. Yao Y, *et al.* Improving nitrogen use efficiency in agriculture: A global perspective. Front Plant Sci. 2019;10:381. https://doi.org/10.3389/fpls.2019.00381
20. Zhang H, *et al.* Improving nitrogen use efficiency in agriculture through improved fertilizer application and crop management practices. Agron Sustain Dev. 2017;37(4):39. https://doi.org/10.1007/s13593-017-0441-0447