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Optimizing Nitrogen Use Efficiency through Modern Agronomic Practices

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ABSTRACT

Nitrogen Use Efficiency (NUE) is a key characteristic for sustainable agriculture to increase crop yield in parallel with reducing negative environmental impacts. Inm-Integrated Nutrient Management: Integrated nutrient management is an approach that integrates both organic and inorganic sources of nutrients & improves the productivity of crops and crop sustainability. Controlled release or stabilized nitrogen fertilizers better match plant needs with nutrient supply and reduce losses. Crop rotation and diversification approaches are used to improve NUE by maintaining soil fertility, pest management, and enhancing crop productivity. Organic amendments are essential in enhancing soil health and can serve as drivers of carbon sequestration as well as facilitate optimized nutrient cycling. There are challenges associated with NUE optimization, regardless of the sophistication of technology. The mentioned requirements are a better linkage between crop and livestock systems, development of more reliable NUE indicators, and adjusting precision farming for the sustainability. The path forward should concentrate on strategies that are innovative like improved crop sequences and sensor-based fertility management systems as well as an intensification which is sustainable. This group of problems required a high level of efficiency in nitrogen use as well as a decent performance of crops and mitigation of environmental degradation. Such holistic approaches combine the agronomic, genetic, and technologic dimensions into a long-term effort to conquer the exigencies of feeding the world's population without adversely affecting ecosystem health.

Key words: *Nitrogen Use Efficiency (NUE), Integrated Nutrient Management (INM), Slow-release fertilizers, Crop rotation, Soil health, Sustainable agriculture*

Introduction

Nitrogen Use Efficiency (NUE) is a crucial aspect of modern agronomic practices aimed at optimizing crop production while minimizing environmental impacts associated with excessive nitrogen fertilizer use. Various studies have highlighted the importance of improving NUE through different approaches, including genetic enhancements, agronomic practices, and technological interventions (Lassaletta *et al.,* 2014). Countries utilizing a higher proportion of nitrogen inputs from symbiotic nitrogen fixation rather than synthetic fertilizers have been shown to achieve better NUE (Lassaletta *et al.,* 2014). This suggests that exploring alternative sources of nitrogen could be beneficial in enhancing NUE in cropping systems.Agricultural practices involving arbuscular mycorrhizae have been discussed as having the potential to improve NUE by reducing nitrogen fertilizer usage (Verzeaux *et al.,* 2017). This indicates that harnessing beneficial soil microorganisms could be a sustainable strategy to enhance NUE in agriculture. Additionally, genetic factors play a significant role in improving NUE in crop plants to increase yields while minimizing nitrogen inputs (Han *et al.,* 2015). This underscores the need for genetic research to develop crop varieties with enhanced NUE. Maize morphophysiological responses to crowding and low nitrogen availability have been studied, emphasizing the essentiality of improving maize NUE and stress tolerance (Boomsma *et al.,* 2009). This suggests that understanding plant responses to nitrogen stress is crucial for developing strategies to enhance NUE in maize production. Moreover, improving NUE in high nitrogen-demanding crops like canola has been highlighted for sustainable agriculture (Williams and Vail, 2021). This underscores the importance of optimizing NUE in specific crop species to achieve sustainable production practices.Improving NUE in rice for sustainable agriculture has been emphasized through strategies that reduce nitrogen fertilizer input (Wang *et al.,* 2022). This indicates that developing NUE-enhancing practices tailored to specific crops like rice is crucial for sustainable agricultural intensification. Furthermore, agronomic and molecular-based approaches, such as the 4R's of nutrient stewardship, have been shown to enhance NUE in cotton production (Chattha *et al.,* 2022). This suggests that adopting comprehensive management practices can effectively improve NUE in different crop systems.Improving agronomic NUE in crops is essential to increase yields without compromising quality or ecosystem health (Quan *et al.,* 2019). This indicates that sustainable intensification strategies should focus on enhancing NUE to meet increasing food demands. Additionally, genetic variation in NUE of wheat cultivars has been highlighted, emphasizing the importance of improving NUE to mitigate soil fertility issues (Lian *et al.,* 2022). This underscores the need for breeding programs to develop wheat varieties with enhanced NUE for sustainable production. Eco-efficient nitrogen management strategies in aerobic rice systems have been discussed, emphasizing the importance of resource conservation practices to enhance NUE (Farooq et al., 2022). This suggests that integrating sustainable practices into rice production can improve NUE and reduce environmental impacts. Maintaining high crop productivity and efficient nutrient use, particularly NUE, are essential for sustainable agriculture (Monostori *et al.,* 2017). This indicates that optimizing NUE is crucial for achieving sustainable intensification in agriculture. In conclusion, optimizing Nitrogen Use Efficiency (NUE) through modern agronomic practices is essential for sustainable crop production. By integrating genetic advancements, agronomic strategies, and technological innovations, it is possible to enhance NUE, increase yields, and reduce environmental impacts associated with nitrogen fertilizer use. Understanding the complex interactions between crops, soil, and management practices is crucial for developing tailored approaches to improve NUE across different cropping systems.

Integrated Nutrient Management (INM)

Integrated Nutrient Management (INM) is a crucial practice in modern agriculture that aims to optimize nitrogen use efficiency in crop production. Efficient nitrogen management is essential for addressing challenges such as food security, environmental degradation, and climate change (Xin *et al.,* 2015). Agriculture significantly impacts nitrogen input into terrestrial systems, with enhancing nitrogen availability being a primary technique to boost crop yields (Norton and Ouyang, 2019). Exploiting Biological Nitrogen Fixation (BNF) is increasingly urgent to meet the food production demands of a growing global population sustainably (Soumaré *et al.,* 2020). Improving nitrogen use efficiency in crops is vital for the economic and environmental sustainability of agriculture (Zhao *et al.,* 2018).Integrated Nutrient Management involves the combined use of organic and inorganic components along with microorganisms to enhance soil conditions, maintain nutrient levels, and promote high crop yields with desired quality (Kushum *et al.,* 2022). This approach integrates mineral fertilizers with organic manures and microbial inoculants to sustain optimal yields and improve soil fertility (Kumar *et al.,* 2021). Implementing an integrated nutrient management system can enhance soil nutrient availability and improve crop productivity (Singh *et al.,* 2022).

Efforts to increase nitrogen use efficiency in agriculture involve strategies like intercropping, which can enhance nitrogen assimilation and improve nitrogen use efficiency indices compared to monocropping (Nasar *et al.,* 2023). Integrated nitrogen management strategies that consider improved fertilizer, soil, and crop management practices are essential to enhance nitrogen efficiency in agriculture (Weisler *et al.,* 2001). Achieving a better nitrogen balance through effective management is crucial to reduce environmental risks, increase nitrogen use efficiency, and maintain crop yields (Zheng *et al.,* 2015). Integrated Nutrient Management is a multifaceted approach that combines various components to optimize nitrogen use efficiency in agriculture. By integrating organic and inorganic inputs, along with microbial interventions, and adopting sustainable practices, it is possible to enhance crop productivity while minimizing environmental impacts.

Use of Slow-Release and Stabilized Nitrogen Fertilizers

Nitrogen is an essential element for plant growth and agricultural productivity. The use of slow-release and stabilized nitrogen fertilizers has gained attention in modern agronomic practices to enhance nitrogen use efficiency and minimize environmental impacts. These fertilizers offer controlled release mechanisms that match plant demand, reducing losses and improving crop yields (Guo *et al*., 2020; Cameron *et al*., 2013; Ribeiro *et al*., 2016; Sunlin, 2018). Slow-release fertilizers, such as rice husk biochar coated urea, have shown promise in providing nutrients gradually to plants (Gamage *et al*., 2021). Additionally, advancements in technology have led to the development of innovative fertilizers like zinc- andmagnesium-doped hydroxyapatite nanoparticles modified with urea, which exhibit optimal nitrogen release patterns (Sharma *et al*., 2022).

Efforts to optimize nitrogen use efficiency involve various strategies, including the application of nitrification and urease inhibitors, fertigation, and precision agriculture techniques (Xin *et al*., 2015). Studies have indicated that slow-release fertilizers, when applied to plants rather than the soil, can help control nitrogen losses and increase crop yields (Raun and Johnson, 1999). Furthermore, the incorporation of stabilized nitrogen fertilizers in agricultural practices has been shown to reduce the carbon footprint associated with fertilization (Hasler *et al*., 2017). The global nitrogen cycle is significantly impacted by anthropogenic activities, with agriculture being a major contributor to reactive nitrogen species in terrestrial ecosystems (Fowler *et al*., 2013). The use of nitrogen fertilizers, especially in coated forms like urea, plays a significant role in agricultural systems, affecting nitrogen transformations and plant nutrient uptake (Glibert *et al*., 2005). Slow-release fertilizers have been found to regulate nitrogen release according to plant needs, contributing to improved productivity (Abdel-Sattar and Mohamed, 2017). The adoption of slow-release and stabilized nitrogen fertilizers presents a promising approach to enhance nitrogen use efficiency, increase crop yields, and mitigate environmental concerns associated with nitrogen fertilization in modern agriculture.

Crop Rotation and Diversification

Crop rotation and diversification are essential components of modern agronomic practices aimed at optimizing nitrogen use efficiency and enhancing sustainability in agricultural systems. Numerous studies have demonstrated the benefits of crop diversification strategies such as crop rotation, intercropping, and multiple cropping in enhancing crop productivity while preserving environmental quality and ecosystem services (Francaviglia *et al*., 2020). Research has shown that crop rotation with species diversification can effectively manage pests, diseases, and weeds, improve soil fertility, and increase profitability in grain production systems (Volsi *et al*., 2022). Moreover, crop diversification through a wider selection of crop varieties has been advocated to enhance resilience and biodiversity in agro ecosystems (Meyer *et al*., 2019).

Nitrogen imbalance in crop application and utilization can result in excess nitrogen in the environment, leading to adverse effects on water and air quality and contributing to climate change (Mueller *et al.*, 2014). Therefore, optimizing nitrogen use efficiency through practices like crop diversification is crucial to mitigate these environmental impacts. Additionally, crop diversification has been recognized as a valuable strategy for sustainable agricultural development, with the goal of enhancing productivity, sustainability, and ecological system supply (Barman *et al*., 2022).

Studies have indicated that crop diversification can lead to increased cropping intensity, higher employment rates, and the commercialization of farming, thereby contributing to overall agricultural development and income stability (Priyanga *et al*., 2023). Furthermore, crop diversification, including crop and forage rotation strategies, has been proposed to stabilize system productivity and profitability by incorporating high-value crops and environmentally sustainable practices (Ramamoorthy and Natarajan, 2020).

Soil Health Management and Organic Amendments

Organic amendments play a crucial role in improving soil health and promoting sustainable agriculture. Here are the key points: Organic amendments increase soil carbon sequestration, which helps mitigate climate change by locking away carbon that could otherwise be released into the atmosphere. Studies show organic soils have significantly higher levels of sequestered carbon compared to conventional soils.

Organic management and soil health promote more efficient use of nutrients like nitrogen. Organically managed soils have higher nitrogen use efficiency (NUE) compared to conventionally managed soils, with NUE positively linked to microbial biomass, soil organic carbon content, and aggregate size. This indicates enhanced soil quality and health leads to more efficient fertilizer use.

The use of organic amendments from agricultural residues contributes to significant enhancement of soil biodiversity, the restoration of soil fertility, and improvement of soil physical properties like structure, porosity, and water-holding capacity. However, there are also some constraints to consider, such as potential contamination, nutrient imbalances, and the need for proper application rates. Organic amendments are a key component of sustainable agriculture, improving soil health, nutrient cycling, and climate change mitigation. While there are some challenges, the benefits of organic amendments in restoring degraded soils and promoting long-term sustainability are well-established.

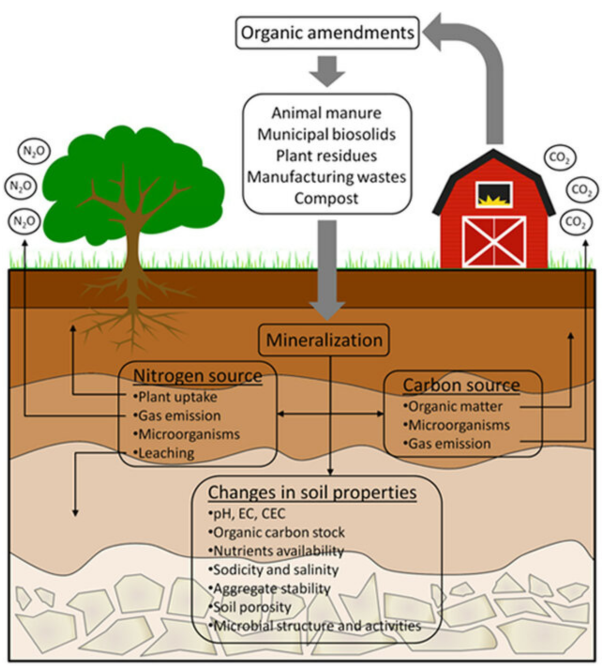

Fig. 1. Schematic representation of the effect of organic amendments on soil properties by acting as a source of carbon and nitrogen (Scotti *et al*., 2014)

Challenges and Future Directions in NUE Optimization

Nitrogen Use Efficiency (NUE) optimization in modern agronomic practices presents various challenges and future directions for sustainable agriculture. One key aspect is the need to enhance NUE at both local and global scales through improved integration of crop and livestock systems (Lassaletta *et al*., 2014). This integration can lead to better fertilizer use and increased efficiency in nitrogen utilization (Iqbal *et al*., 2019). Additionally, optimizing crop rotations, sensor-based fertilizer adjustments, and enhancing the intrinsic NUE of crops are crucial steps in addressing the challenge of NUE optimization (Bouchet *et al.,* 2016).

Mitigating nitrous oxide emissions from fertilized cropping systems is another significant challenge that requires maximizing the utilization of added fertilizer to optimize crop NUE (Venterea *et al*., 2012). Protecting the environment while maximizing yield and quality through improved NUE in crop systems is a primary challenge in modern agriculture (Gioia *et al*., 2017). Developing robust NUE indicators for entire food systems is essential for policy development and monitoring progress in enhancing NUE (Erisman *et al*., 2018). Furthermore, challenges in winter wheat production include optimizing nitrogen management for high crop yield and NUE across different soil landscapes and weather conditions (Li *et al.,* 2022). Excessive fertilizer use in conventional agriculture and extreme spatial differences in N balance pose challenges for N management, emphasizing the need for comprehensive farm nitrogen management systems (Weckesser *et al*., 2021). Exploring crop variety and soil N cycling can further improve plant NUE (Williams and Vail, 2021).

To address the challenge of excessive nitrogen fertilizer application in intensive vegetable production, an integrated nitrogen management strategy is essential to promote crop yield, nitrogen uptake, and NUE (Ma *et al*., 2022). Achieving high NUE and crop productivity amidst increased global food de-

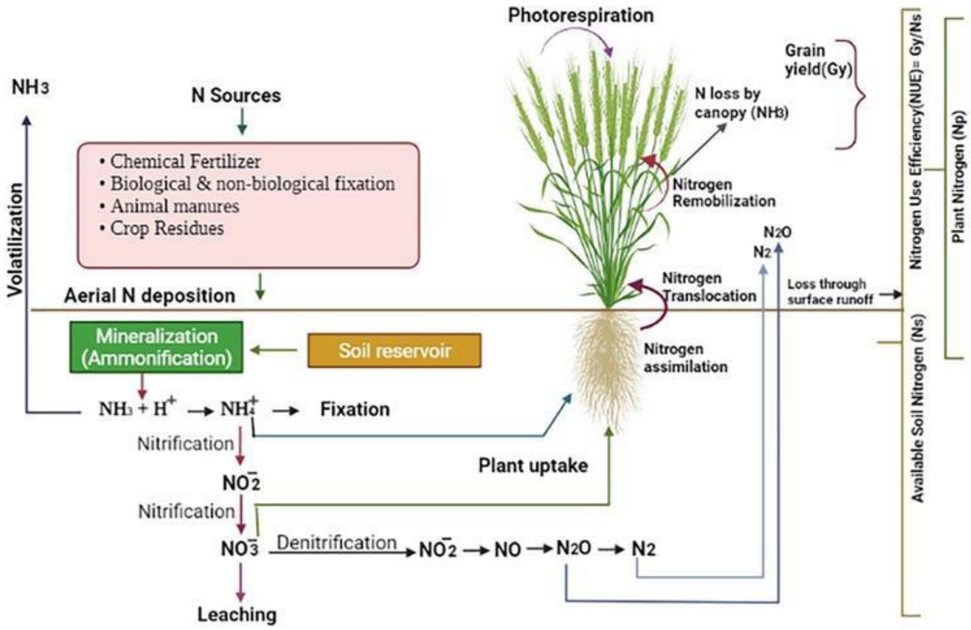

Fig. 1. Schematic representation of the relationship between the nitrogen sources, uptake, utilization, and conversion to the wheat grain yield (Prakash Raigar *et al.*, 2022)

mand and environmental degradation requires innovative strategies and approaches (Ebbisa, 2022). Balancing plant density and nitrogen application is crucial to manipulate tiller growth and increase grain yield and NUE in winter wheat (Yang *etal*., 2019). Improving NUE through agronomic and molecular-based approaches in cotton production highlights the importance of irrigation methods, fertilizer application, and hybrid selection in enhancing NUE (Chattha *et al*., 2022). Effective N management systems, updated application guidelines, and improved NUE are key challenges in sustaining wheat production (Walsh and Christiaens, 2016). Investigating various traits and parameters related to NUE in wheat is essential for climate-resilient agriculture (Gayatri *et al.*, 2024).

Resource conservation practices and precision farming play a vital role in enhancing NUE in aerobic rice systems (Farooq *et al*., 2022). Maximizing maize N efficiency in saline soils through integrated N amount and sources is a challenge that requires understanding the effects of different N sources on crop NUE (Miao *et al.*, 2021).

Conclusion

Optimizing Nitrogen Use Efficiency (NUE) is pivotal for sustainable agriculture, balancing the need for high crop yields with the imperative to reduce environmental impacts. This optimization involves a multifaceted approach, integrating genetic advancements, agronomic practices, and technological innovations. Improving NUE begins at the genetic level. Developing crop varieties with enhanced NUE through genetic research is critical. This involves breeding plants that require less nitrogen and can thrive in lower nitrogen environments. For instance, maize and wheat varieties with higher NUE can produce more with less fertilizer, reducing the environmental footprint. Genetic enhancements must be complemented by agronomic practices tailored to specific crops. For example, rice cultivation benefits from strategies that reduce nitrogen fertilizer input while maintaining high yields. Similarly, canola and cotton production can be optimized by adopting the 4R's of nutrient stewardship: the right source, right rate, right time, and right place.

Integrated Nutrient Management (INM) combines organic and inorganic fertilizers with microbial inoculants to sustain optimal yields and improve soil fertility. This approach not only enhances NUE but also promotes soil health. INM involves the use of mineral fertilizers, organic manures, and microbial interventions to create a balanced nutrient supply, ensuring that crops receive adequate nutrition throughout their growth stages. The integration of these components can lead to improved soil structure, increased microbial activity, and enhanced nutrient availability, contributing to higher crop productivity and environmental sustainability.

Slow-release and stabilized nitrogen fertilizers are innovative solutions that improve NUE by aligning nitrogen release with plant demand. These fertilizers reduce nitrogen losses through leaching and volatilization, thereby enhancing nutrient uptake by plants. For instance, rice husk biochar-coated urea and zinc- and magnesium-doped hydroxyapatite nanoparticles are examples of advanced fertilizers that provide a steady nutrient supply. These technologies not only improve crop yields but also mitigate the environmental impacts associated with nitrogen fertilization. Crop rotation and diversification are essential strategies for optimizing NUE. By alternating different crops in a sequence, farmers can manage soil fertility, control pests and diseases, and improve soil structure. Crop diversification, including intercropping and multiple cropping, enhances nitrogen assimilation and utilization, thereby reducing the need for synthetic fertilizers. This practice also increases biodiversity, resilience, and overall sustainability of agro ecosystems. Soil health management through organic amendments is another critical aspect of improving NUE. Organic amendments such as compost, manure, and cover crops enhance soil organic matter, microbial activity, and nutrient cycling. These improvements lead to better soil structure, increased water-holding capacity, and more efficient use of nitrogen. Organic amendments also contribute to carbon sequestration, helping mitigate climate change by storing carbon in the soil. Challenges in optimizing NUE include managing nitrous oxide emissions, a potent greenhouse gas, from fertilized fields. Strategies to mitigate these emissions involve improving fertilizer application methods, adopting precision agriculture techniques, and enhancing the intrinsic NUE of crops. Developing robust NUE indicators is essential for monitoring progress and guiding policy decisions. Additionally, integrating crop and livestock systems can improve nutrient recycling and overall efficiency. Future directions in NUE optimization involve advancing precision agriculture, which uses sensors, data analytics, and automation to apply fertilizers more accurately and efficiently. Research into crop genetics, soil microbiology, and nutrient management will continue to play a crucial role. Sustainable intensification strategies that increase productivity while preserving environmental quality are vital to meeting global food demands.

Conflict of Interest- None

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