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Enhancing Nitrogen Use Efficiency in Rice for Sustainable Agriculture

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Abstract The primary goal of this study is to enhance nitrogen use efficiency (NUE) in rice (*Oryza sativa* L.) to promote sustainable agricultural practices. This involves reducing the dependency on nitrogen fertilizers while maintaining or improving rice productivity and minimizing environmental impacts. Key discoveries include the identification of genetic and agronomic strategies to improve NUE. Genetic approaches, such as the manipulation of NIN-like proteins (OsNLP1 and OsNLP3), have shown promise in enhancing NUE and grain yield under varying nitrogen conditions. Additionally, site-specific nutrient management (SSNM) and digital decision support tools like Rice Crop Manager have been effective in optimizing nitrogen application, thereby improving NUE and reducing environmental pollution. The integration of conventional breeding, molecular genetics, and alternative farming techniques has also been highlighted as essential for achieving sustainable improvements in NUE. The findings underscore the importance of a multifaceted approach combining genetic, agronomic, and technological innovations to enhance nitrogen use efficiency in rice. These strategies not only improve rice productivity but also contribute to environmental sustainability by reducing nitrogen losses and pollution. Future research should focus on refining these approaches and promoting their adoption among farmers to achieve long-term sustainability in rice production.

Keywords Nitrogen use efficiency; Rice (*Oryza sativa* L.); Sustainable agriculture; Genetic improvement; Site-specific nutrient management; Environmental sustainability

1 Introduction

Rice (*Oryza sativa* L.) is a fundamental staple food crop for more than half of the global population, playing a crucial role in food security worldwide (Lee, 2021; Farooq et al., 2022). As the global population continues to grow, the demand for rice is expected to increase, making it essential to enhance rice productivity to meet future food requirements (Huang et al., 2018; Lee, 2021). The significance of rice in global food security cannot be overstated, as it provides a primary source of calories and nutrition for billions of people (Lee, 2021; Farooq et al., 2022).

Nitrogen (N) is a vital nutrient for the growth and development of rice, significantly influencing its yield and quality (Huang et al., 2018; Farooq et al., 2022). The application of N fertilizers has been a common practice to boost rice productivity; however, excessive use of N fertilizers has led to several environmental and economic challenges (Lee, 2021; Farooq et al., 2022). Over-application of N fertilizers results in nutrient losses through leaching, volatilization, and runoff, contributing to environmental pollution and greenhouse gas emissions. Additionally, the inefficient use of N fertilizers increases production costs and reduces the overall sustainability of rice farming (Chivenge et al., 2021; Farooq et al., 2022).

Improving nitrogen use efficiency (NUE) in rice is critical for reducing the environmental impact of N fertilization and enhancing the sustainability of rice production systems (Huang et al., 2018; Lee, 2021; Farooq et al., 2022). Enhanced NUE can lead to reduced N losses, lower greenhouse gas emissions, and decreased water pollution, thereby promoting environmental sustainability. Furthermore, improving NUE can help maintain or even increase rice yields while reducing the dependency on chemical fertilizers, thus supporting economic sustainability for farmers (Chivenge et al., 2021; Farooq et al., 2022). Strategies such as site-specific nutrient management (SSNM), integrated nutrient management (INM), and the use of N-efficient rice varieties are essential for achieving higher NUE and sustainable rice production (Huang et al., 2018; Chivenge et al., 2021; Farooq et al., 2022).

This research aims to explore and develop strategies to enhance nitrogen use efficiency in rice, focusing on both agronomic practices and genetic improvements. The study will explore the role of nitrogen in rice growth, challenges in nitrogen application, and potential solutions to improve NUE, in an effort to provide comprehensive insights on optimizing nitrogen use in rice cultivation, ultimately promoting sustainable agricultural development and global food security.

2 Current Nitrogen Use Practices in Rice Farming

2.1 Conventional nitrogen fertilization methods

In rice cultivation, conventional nitrogen (N) fertilization methods typically involve the application of nitrogenous fertilizers in various forms such as urea, ammonium sulfate, and nitrate-based fertilizers. The application rates of these fertilizers can vary significantly depending on the region, soil type, and specific crop requirements. Generally, farmers apply nitrogen fertilizers at rates ranging from 100 to 300 kg N/ha, with the timing of application being crucial to maximize nitrogen use efficiency (NUE) and crop yield. Commonly, nitrogen is applied in multiple split doses: a basal dose before or at the time of planting, followed by top-dressings at critical growth stages such as tillering and panicle initiation (Lee, 2021; Shrestha et al., 2022) (Figure 1).

Figure 1 A farmer manually applying nitrogen fertilizer in a paddy field, illustrating conventional nitrogen management practices in rice farming. This reflects the common split-application method, where nitrogen is applied during key growth stages such as tillering to enhance nitrogen use efficiency (NUE) and crop yield (Photo from Zhigang Fu)

The forms of nitrogen used in rice farming also play a significant role in determining the efficiency of nitrogen uptake by the plants. Conventional methods often involve surface broadcasting of prilled urea, which is prone to significant nitrogen losses through volatilization, leaching, and runoff. To mitigate these losses, some farmers have adopted deep placement techniques, where nitrogen fertilizers are placed deeper in the soil, closer to the root zone, thereby enhancing nitrogen availability and reducing losses (Baral et al., 2020; Khalofah et al., 2021). Despite these efforts, the overall NUE in conventional rice farming remains relatively low, necessitating the exploration of more efficient fertilization strategies.

2.2 Global trends in nitrogen use

Globally, nitrogen application practices in rice farming exhibit considerable regional differences, influenced by factors such as local agronomic practices, soil fertility, and economic constraints. In developed countries, precision agriculture techniques and advanced fertilization methods are increasingly being adopted to optimize nitrogen use and minimize environmental impacts. For instance, the use of slow-release fertilizers and nitrification inhibitors is becoming more common, helping to improve NUE and reduce nitrogen losses (Ding et al., 2020; Wang et al., 2022).

In contrast, developing countries often face challenges related to over-reliance on conventional nitrogen fertilizers and lack of access to advanced technologies. In regions like China, where rice is a staple crop, farmers tend to apply excessive amounts of nitrogen fertilizers to ensure high yields, leading to significant environmental pollution and economic inefficiencies (Hu et al., 2023). Efforts are being made to promote balanced fertilization and integrated nutrient management practices, but widespread adoption remains limited due to socio-economic barriers and lack of awareness (Qiu et al., 2022; Shrestha et al., 2022). Addressing these challenges requires concerted efforts to educate farmers, improve access to advanced fertilization technologies, and implement policies that encourage sustainable nitrogen use.

2.3 Environmental impacts of excess nitrogen

The excessive use of nitrogen fertilizers in rice farming has profound environmental impacts, including soil degradation, water contamination, and greenhouse gas emissions. High rates of nitrogen application can lead to the accumulation of nitrates in the soil, which can subsequently leach into groundwater, posing risks to human health and aquatic ecosystems. Additionally, nitrogen runoff from rice fields can contribute to the eutrophication of water bodies, leading to algal blooms and the depletion of oxygen levels, which adversely affect aquatic life (Qiu et al., 2022; Shrestha et al., 2022).

Moreover, the volatilization of ammonia and the emission of nitrous oxide (N_2O) from rice fields are significant contributors to air pollution and climate change. Nitrous oxide is a potent greenhouse gas with a global warming potential approximately 300 times that of carbon dioxide. Studies have shown that conventional nitrogen fertilization methods, particularly surface broadcasting, result in higher N_2O emissions compared to more efficient practices such as deep placement of nitrogen fertilizers (Baral et al., 2020; Li et al., 2021). Therefore, improving NUE and adopting environmentally friendly fertilization practices are critical for mitigating the adverse environmental impacts of nitrogen use in rice farming.

3 Genetic Approaches to Enhancing NUE in Rice

3.1 Genetic variability for NUE

Identification of genetic variation in rice varieties for nitrogen uptake and utilization is crucial for improving nitrogen use efficiency (NUE). Studies have shown significant genetic variability in NUE among different rice varieties, particularly in rainfed upland conditions. For instance, research conducted in Madagascar with 13 tropical japonica rice varieties revealed substantial genetic variability for NUE, nitrogen uptake efficiency (NUPE), and nitrogen utilization efficiency (NUTE) under both high and low nitrogen conditions (Rakotoson et al., 2017). This variability is essential for breeding programs aimed at enhancing NUE, as it provides a pool of genetic resources that can be exploited to develop rice varieties with superior nitrogen uptake and utilization capabilities.

Moreover, the genetic variability in NUE is influenced by environmental factors such as rainfall distribution, which affects nitrogen availability and uptake. The study in Madagascar highlighted the significant Year × N and Year × G interactions due to varying rainfall patterns across different cropping seasons, further emphasizing the complexity of NUE as a trait (Rakotoson et al., 2017). Understanding these interactions is vital for developing rice varieties that can maintain high NUE under diverse environmental conditions.

3.2 Key genes and pathways involved in NUE

The role of nitrate transporters, nitrogen assimilation enzymes, and regulatory genes is pivotal in enhancing NUE in rice. Nitrate transporters such as OsNPF6.1 have been identified as key players in nitrate uptake and NUE. A genome-wide association study identified an elite haplotype of OsNPF6.1, which enhances nitrate uptake and confers high NUE by increasing yield under low nitrogen supply (Tang et al., 2019). This transporter is differentially trans-activated by the transcription factor OsNAC42, highlighting the importance of regulatory networks in NUE.

Additionally, nitrogen assimilation enzymes and regulatory genes such as OsNLP1 and OsNLP3 play crucial roles in NUE. OsNLP1 rapidly responds to nitrogen deficiency and improves yield and NUE by regulating multiple nitrogen uptake and assimilation genes (Alfatih et al., 2020) (Figure 2). Similarly, OsNLP3 modulates NUE and grain yield under nitrate-sufficient conditions by orchestrating the expression of nitrogen uptake and assimilation genes (Zhang et al., 2022). These findings underscore the complex regulatory networks involving transporters, enzymes, and transcription factors that govern NUE in rice.

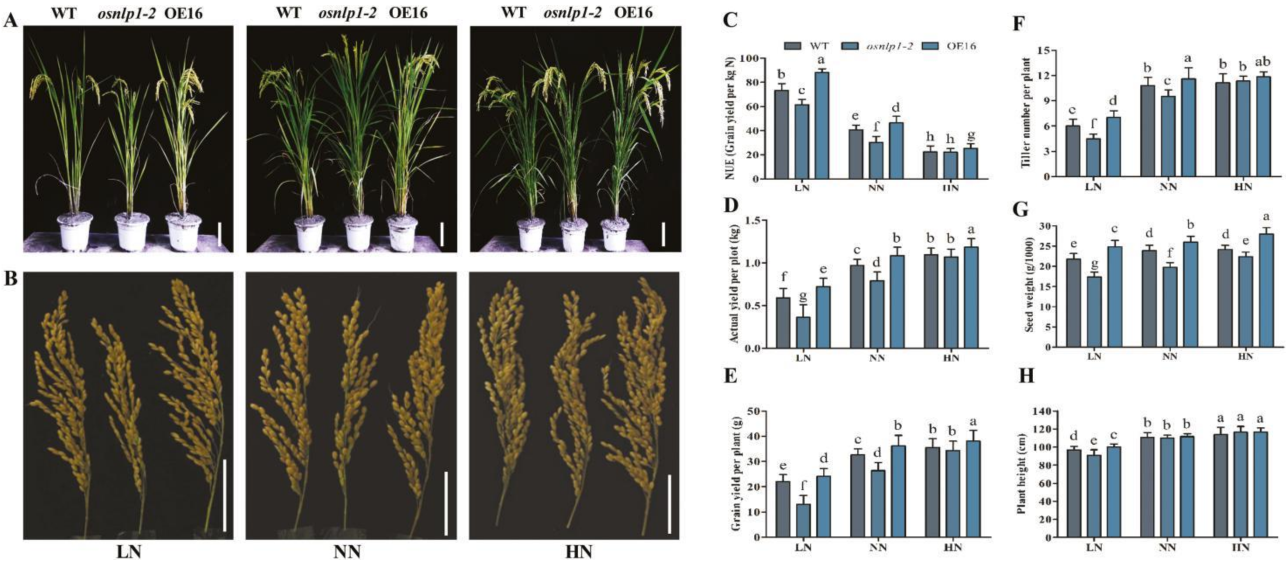

Figure 2 OsNLP1 improves grain yield in the field under different nitrogen levels (Adopted from Alfatih et al., 2020)

Image caption: (A) Growth status of a representative WT (ZH11), *osnlp1-2* mutant, and OE16 plant grown in the field in low nitrogen (LN), normal nitrogen (NN), and high nitrogen (HN) conditions. The plants were dug out from the field and potted for photography. Scale bar: 10 cm. (B) A representative panicle of WT (ZH11), *osnlp1-2*, and OE16 plants. Scale bar: 8 cm. (C-H) Agronomic traits. Nitrogen use efficiency (NUE), actual yield per plot, grain yield per plant, seed weight (g/1000), tiller number, and plant height were statistically analysed. Values are the means and SD (30 plants per replicate with three replicates). Different letters denote significant differences ($P<0.05$) from Duncan's multiple range test. (This figure is available in color at JXB online.) (Adopted from Alfatih et al., 2020)

3.3 Molecular breeding for NUE improvement

Advances in genomic tools such as quantitative trait locus (QTL) mapping, gene editing, and CRISPR-Cas9 have significantly contributed to enhancing nitrogen efficiency in rice varieties. QTL mapping has been instrumental in identifying chromosomal hotspots and candidate genes associated with NUE. For example, a meta-analysis of yield-related and N-responsive genes in rice identified 1 064 NUE-related genes, including 80 transporters and 235 transcription factors, which were further shortlisted to 62 candidate genes through hierarchical methods (Kumari et al., 2021). These genes are localized to specific chromosomes, with chromosome 1 emerging as a hotspot for NUE.

Gene editing technologies like CRISPR-Cas9 have also shown promise in improving NUE. By targeting specific genes involved in nitrogen uptake and assimilation, researchers can create rice varieties with enhanced NUE. For instance, the modulation of the DNR1 gene, which is involved in auxin homeostasis, has been shown to improve NUE and grain yield in rice (Zhang et al., 2020). These molecular breeding approaches offer new avenues for developing rice varieties that require less nitrogen fertilizer while maintaining high productivity, thereby contributing to sustainable agriculture.

4 Agronomic Strategies to Improve NUE

4.1 Optimizing fertilizer application

Optimizing the timing, method, and form of nitrogen (N) application is crucial for enhancing nitrogen use efficiency (NUE) in rice cultivation. Split application of N fertilizers, where the total N dose is divided into multiple smaller doses applied at different growth stages, has been shown to improve NUE by synchronizing N availability with the crop's demand (Wang et al., 2022). This method reduces N losses through leaching and volatilization, thereby increasing the efficiency of N uptake by the plants. Controlled-release fertilizers (CRFs), such as polymeric-coated urea, have also demonstrated significant improvements in NUE. These fertilizers release N gradually, matching the crop's uptake pattern and minimizing environmental losses. For instance, a study found that CRFs increased rice yields by approximately 35% compared to traditional fertilizers, while also enhancing leaf N content and other essential nutrients (Gil-Ortiz et al., 2020) (Figure 3).

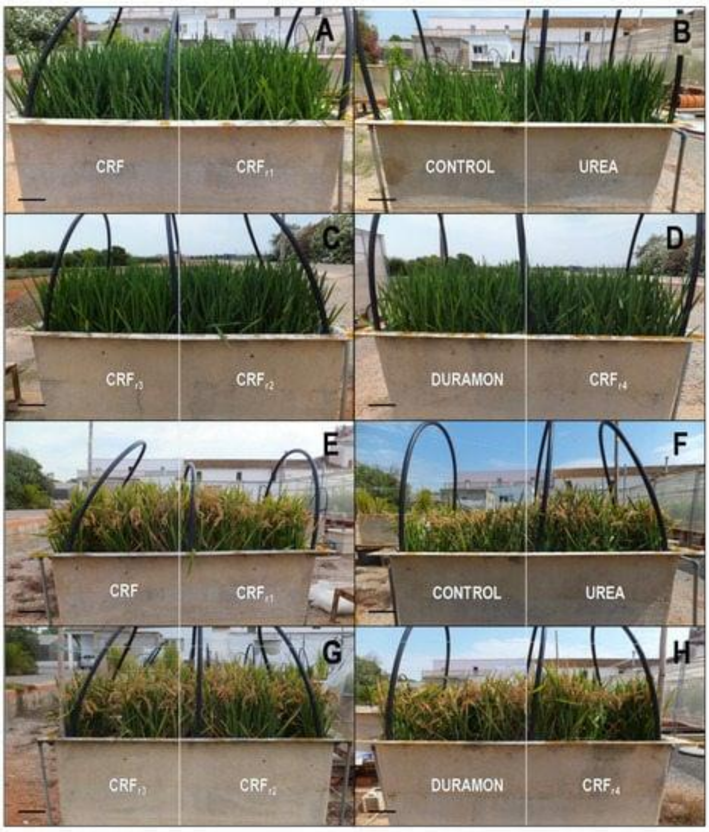

Figure 3 Comparison of rice growth responses, on the microscale experiment, to the applied CRF and their reductions from CRF$_{r1}$ to CRF$_{r4}$, DURAMON®, UREA, and the CONTROL (no fertilizer applied) in the phenological stage of booting (A-D) and at the end of culture (E,F). Treatments from left to right: CRF, CRF$_{r1}$ (A,E); CONTROL, NSA (B,F); CRF$_{r3}$, CRF$_{r2}$ (C,G); DURAMON®, CRF$_{r4}$ (D,H). Bars correspond to 10 cm (Adopted from Gil-Ortiz et al., 2020)

Additionally, site-specific nutrient management (SSNM) tools like Rice Crop Manager and Nutrient Expert have been developed to provide tailored fertilizer recommendations based on local conditions and crop needs. These digital tools help farmers apply the right amount of N at the right time, further improving NUE and reducing environmental impacts (Chivenge et al., 2021). Despite the proven benefits, the adoption of these advanced fertilization techniques remains low, necessitating policy support and extension services to encourage wider use among farmers.

4.2 Water and nitrogen management

Effective irrigation practices play a significant role in enhancing NUE in rice cultivation. Alternate wetting and drying (AWD) is an irrigation technique that has been shown to improve both water and nitrogen use efficiency. AWD involves periodically allowing the soil to dry before re-irrigating, which reduces water usage and minimizes N losses through denitrification and leaching (Santiago-Arenas et al., 2021). Studies have demonstrated that AWD can achieve similar grain yields to continuous flooding while saving 40%~44% of water and increasing water productivity by 68%.

Moreover, integrating AWD with optimized N application rates can further enhance NUE. For example, applying 60 kg N ha^{-1} under AWD conditions resulted in higher partial factor productivity of N compared to higher N rates, indicating more efficient use of applied N (Santiago-Arenas et al., 2021). This approach not only reduces the environmental footprint of rice cultivation but also lowers input costs, making the practice more sustainable and economically viable for farmers.

4.3 Integrated nutrient management (INM)

Integrated Nutrient Management (INM) combines the use of organic fertilizers, biological inoculants, and chemical fertilizers to optimize nitrogen availability and improve NUE. This holistic approach leverages the strengths of different nutrient sources to enhance soil fertility and crop productivity. Organic fertilizers, such as compost and manure, improve soil structure and microbial activity, which in turn enhances N mineralization and availability to plants (Novair et al., 2021). Biological inoculants, including nitrogen-fixing bacteria and mycorrhizal fungi, further contribute to N uptake and utilization by the rice plants.

Combining these organic and biological inputs with chemical fertilizers ensures a balanced nutrient supply throughout the growing season. For instance, the use of controlled-release N fertilizers in conjunction with organic amendments has been shown to significantly improve NUE and reduce N losses (Novair et al., 2021). Field experiments have demonstrated that deep placement of briquetted urea, a form of controlled-release fertilizer, increased grain yields by 21%~23% and improved various NUE metrics compared to traditional broadcast methods (Baral et al., 2020). This integrated approach not only enhances NUE but also promotes sustainable agricultural practices by reducing reliance on chemical fertilizers and mitigating environmental pollution.

5 Microbial and Rhizosphere Interventions for Enhancing NUE

5.1 Role of soil microorganisms

Soil bacteria and fungi play a crucial role in influencing nitrogen availability and uptake in rice plants. The rhizosphere, the narrow region of soil influenced by root secretions and associated soil microorganisms, is a hotspot for microbial activity that significantly impacts nitrogen cycling. Soil microorganisms, including bacteria and fungi, contribute to various nitrogen transformations such as ammonification, nitrification, and nitrogen fixation. For instance, the inoculation of rice plants with *Azospirillum brasilense* and *Pseudomonas fluorescens* has been shown to enhance ammonification and nitrogenase activities in the rhizosphere, thereby increasing the nitrogen supply capacity and improving rice grain yields (Junhua et al., 2021). Additionally, the application of nitrogen fertilizers can alter the microbial community structure in the rhizosphere, affecting the balance between nitrifying and denitrifying bacteria, which in turn influences nitrogen availability for plant uptake (Chen et al., 2019).

Moreover, soil microorganisms can modulate the rhizosphere priming effect (RPE), a phenomenon where root exudates stimulate microbial turnover and the decomposition of soil organic matter, thereby affecting nitrogen dynamics. Nitrogen fertilization has been found to reduce microbial carbon-to-nitrogen (C:N) imbalance and soil pH, which can influence microbial metabolic efficiency and turnover time, ultimately regulating the RPE and nitrogen availability in paddy soils (Chen et al., 2021). These interactions highlight the importance of understanding and managing soil microbial communities to enhance nitrogen use efficiency (NUE) in rice cultivation.

5.2 Inoculants for nitrogen fixation

The use of nitrogen-fixing bacteria, such as Azospirillum and Rhizobium, holds significant potential for improving NUE in rice. These bacteria can convert atmospheric nitrogen into a form that plants can readily absorb, reducing the need for chemical nitrogen fertilizers. Inoculation with nitrogen-fixing bacteria like *Azospirillum brasilense* has been shown to enhance nitrogenase activity in the rhizosphere, particularly under lower nitrogen application rates, thereby contributing to a more sustainable nitrogen supply for rice plants (Junhua et al., 2021). Similarly, *Pseudomonas stutzeri* A1501 has been demonstrated to improve plant growth and nitrogen content in maize by increasing the population of indigenous diazotrophs and ammonia oxidizers in the rhizosphere (Ke et al., 2019).

The application of these inoculants not only enhances nitrogen fixation but also positively influences the overall microbial community structure in the rhizosphere. For example, inoculation with nitrogen-fixing bacteria can lead to a shift in the microbial community towards a dominance of beneficial diazotrophic bacteria, which further supports nitrogen cycling and plant growth (Ke et al., 2019). This approach offers a promising strategy for reducing dependency on chemical fertilizers and promoting sustainable agricultural practices.

5.3 Microbial inoculants and biofertilizers

The application of biofertilizers, which contain living microorganisms, can significantly boost microbial activity and optimize nitrogen cycling in rice paddies. Biofertilizers such as those containing Azospirillum, Rhizobium, and Bacillus species have been shown to enhance plant growth by improving nitrogen availability and uptake. For instance, the co-inoculation of rice seedlings with *Azospirillum brasilense* and *Pseudomonas fluorescens* has been found to significantly enhance ammonification and nitrogenase activities in the rhizosphere, leading to improved nitrogen supply and rice grain yields (Junhua et al., 2021). Additionally, biofertilizers can increase microbial biomass and soil enzyme activities, which are critical for efficient nitrogen cycling and plant nutrition (Yu et al., 2018).

Moreover, biofertilizers can help mitigate the negative environmental impacts associated with excessive chemical nitrogen fertilization. By promoting the growth of beneficial microorganisms that enhance nitrogen fixation and reduce nitrogen losses through denitrification, biofertilizers contribute to a more sustainable and eco-friendly agricultural system. For example, the combined application of biochar and nitrogen fertilizer has been shown to increase microbial biomass and nitrogen retention in the rhizosphere, thereby improving soil fertility and reducing nitrogen leaching (Yu et al., 2018). These findings underscore the potential of microbial inoculants and biofertilizers in enhancing NUE and supporting sustainable rice production.

6 Technological Innovations for Monitoring and Managing NUE

6.1 Precision agriculture tools

Precision agriculture tools, such as remote sensing, drones, and soil sensors, have revolutionized the monitoring and management of nitrogen use efficiency (NUE) in rice cultivation (Figure 4). Remote sensing technologies, including unmanned aerial vehicles (UAVs), provide a non-destructive means to assess crop nitrogen status in real-time. UAV-based remote sensing can collect spectral reflectance imagery, which is crucial for precision nitrogen management. Machine learning methods, such as random forest algorithms, have been shown to significantly improve the estimation of rice nitrogen nutrition indices, thereby enhancing the accuracy of nitrogen management recommendations (Zha et al., 2020; Liang et al., 2021) (Figure 5).

Figure 4 A drone (UAV) conducting remote sensing over a rice field to monitor crop nitrogen status in real time (Photo from Zhigang Fu)

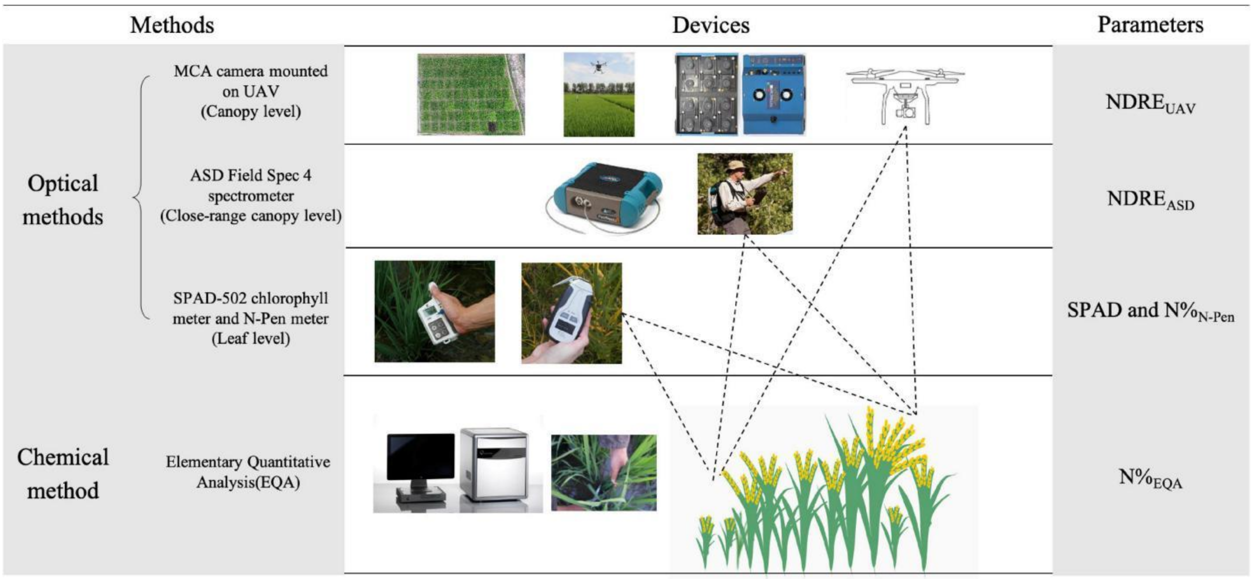

Figure 5 Schematic overview of measured parameters by different methods and devices (Adopted from Liang et al., 2021)

Image caption: NDRE, Normalized Difference Red Edge Index; NDRE$_{UAV}$, NDRE calculated with the canopy reflectance obtained by UAV; NDRE$_{ASD}$, NDRE calculated with the close-range canopy reflectance obtained by ASD; SPAD, SPAD value measured by SPAD-502 chlorophyll meter; N%$_{N-Pen}$, nitrogen content measured by N-pen meter; N%$_{EQA}$, nitrogen content measured by elementary quantitative analysis (EQA) (Adopted from Liang et al., 2021)

Soil sensors also play a critical role in precision agriculture by providing real-time data on soil nitrogen levels. This information allows for site-specific nitrogen management, which can optimize nitrogen application rates and timings to match crop needs more precisely. Studies have demonstrated that integrating UAV data with soil nitrogen content can improve the spatial and temporal variability understanding of nitrogen status in crops, leading to more efficient nitrogen use and reduced environmental impact (Argento et al., 2020).

6.2 Nutrient mapping and decision support systems

Nutrient mapping and decision support systems are essential components of precision nitrogen management. Variable rate technology (VRT) and GIS-based models enable the precise application of nitrogen fertilizers based on the spatial variability of soil and crop nitrogen status. These technologies help in creating detailed nutrient maps that guide the application of nitrogen at variable rates, ensuring that each part of the field receives the optimal amount of fertilizer (Argento et al., 2020; Blaise, 2021).

Decision support systems (DSS) integrate various data sources, including remote sensing, soil sensors, and weather data, to provide real-time recommendations for nitrogen management. These systems can predict the nitrogen requirements of crops at different growth stages and under varying environmental conditions, thereby improving NUE. For instance, studies have shown that using DSS in conjunction with UAV-based remote sensing can lead to significant reductions in nitrogen fertilizer use while maintaining or even increasing crop yields (Argento et al., 2020; Zha et al., 2020).

6.3 Smart fertilization technologies

Smart fertilization technologies, such as slow-release and controlled-release nitrogen products, are designed to improve NUE by synchronizing nitrogen release with crop demand. These fertilizers release nitrogen gradually over time, reducing losses due to volatilization, leaching, and denitrification. The use of nitrification inhibitors and urease inhibitors further enhances the efficiency of nitrogen fertilizers by slowing down the conversion processes that lead to nitrogen losses (Alam et al., 2023; Vijayakumar et al., 2023).

The development of nanofertilizers represents another innovative approach to smart fertilization. Nanofertilizers have a higher surface area and can be engineered to release nutrients in a controlled manner, improving the uptake efficiency by plants. Integrating these advanced fertilization technologies with precision agriculture tools and decision support systems can lead to substantial improvements in NUE, contributing to more sustainable rice production (Blaise, 2021; Vijayakumar et al., 2023).

7 Breeding and Biotechnology Innovations

7.1 Advances in crop breeding

Enhancing nitrogen use efficiency (NUE) in rice through breeding has seen significant advancements with both traditional and modern techniques. Traditional breeding methods, such as hybridization, have been instrumental in developing rice varieties with improved NUE by selecting for traits that enhance nitrogen uptake, assimilation, and remobilization (Lee, 2021; Hou et al., 2021). These methods rely on phenotypic selection and have been successful in identifying and propagating rice varieties that perform better under low nitrogen conditions.

Modern breeding techniques, such as marker-assisted selection (MAS), have further refined the process by allowing for the precise selection of genetic markers associated with high NUE traits. MAS has enabled breeders to identify and select for specific genes that control nitrogen metabolism, leading to the development of rice varieties that are more efficient in nitrogen use (Nguyen and Kant, 2018; Xing et al., 2023). This approach not only accelerates the breeding process but also increases the accuracy of selecting desirable traits, thereby enhancing the overall efficiency of breeding programs aimed at improving NUE in rice.

7.2 Biotechnological interventions

Biotechnological interventions, including genetic modification and gene editing, have opened new avenues for enhancing NUE in rice. Genetic modification techniques have been used to introduce genes that improve nitrogen uptake and assimilation, resulting in rice varieties with higher NUE (Dellero, 2020; Hou et al., 2021). For instance, the introduction of genes that regulate nitrate transport and assimilation has shown promising results in improving NUE and grain yield in rice.

Gene editing technologies, such as CRISPR-Cas9, have revolutionized the field by allowing for precise modifications of the rice genome to enhance NUE. CRISPR-Cas9 has been used to target and edit specific genes involved in nitrogen metabolism, leading to the development of rice varieties with improved nitrogen uptake and utilization (Fiaz et al., 2021). This technology has the potential to create rice varieties that are not only more efficient in nitrogen use but also more resilient to varying environmental conditions, thereby contributing to sustainable agriculture.

7.3 Challenges and future prospects in breeding for NUE

While significant progress has been made in breeding for improved NUE, several challenges remain. One of the primary hurdles is the complexity of nitrogen metabolism, which involves multiple genes and regulatory networks (Lee, 2021; Hou et al., 2021). This complexity makes it difficult to identify and manipulate all the genetic factors involved in NUE. Additionally, the interaction between genetic and environmental factors further complicates the breeding process.

Regulatory and public acceptance issues also pose significant challenges to the adoption of genetically modified and gene-edited rice varieties. Despite the potential benefits, there is still considerable resistance to the use of these technologies in agriculture due to concerns about safety, ethics, and environmental impact (Fiaz et al., 2021). Addressing these concerns through transparent communication and robust regulatory frameworks is essential for the successful implementation of biotechnological interventions in rice breeding.

Looking forward, the integration of advanced breeding techniques with biotechnological interventions holds great promise for improving NUE in rice. Continued research into the genetic basis of NUE, coupled with the development of high-throughput phenotyping and genotyping technologies, will accelerate the breeding process and enhance the efficiency of selecting for high NUE traits (Nguyen and Kant, 2018; Xing et al., 2023). By overcoming the existing challenges and leveraging the latest technological advancements, it is possible to develop rice varieties that contribute to sustainable agriculture and food security.

8 Challenges and Future Prospects

8.1 Barriers to widespread adoption

The adoption of nitrogen use efficiency (NUE)-enhancing practices and technologies in rice farming faces several economic, social, and policy challenges. Economically, the initial costs of implementing advanced NUE technologies, such as precision farming tools and slow-release fertilizers, can be prohibitive for smallholder farmers, who often operate with limited financial resources (Xie et al., 2020; Chivenge et al., 2021). Additionally, the lack of immediate financial returns from these investments can deter farmers from adopting these practices, despite their long-term benefits (Xie et al., 2020).

Socially, there is a significant knowledge gap among farmers regarding the benefits and proper application of NUE-enhancing practices. Many farmers continue to rely on traditional methods of nitrogen application, which are often inefficient and environmentally harmful (Chivenge et al., 2021; Wang et al., 2022). Furthermore, the aging farming population and low levels of education in rural areas exacerbate the challenge of disseminating new agricultural technologies and practices (Xie et al., 2020). Policy-wise, there is often a lack of supportive frameworks and incentives from governments to encourage the adoption of sustainable nitrogen management practices. In many regions, agricultural policies do not prioritize or adequately support the transition to more efficient nitrogen use, leading to continued reliance on conventional, less sustainable methods (Chivenge et al., 2021).

8.2 Research gaps and future directions

Despite significant advancements in understanding and improving NUE in rice, several research gaps remain. One major area that requires further exploration is the impact of climate change on nitrogen dynamics and rice productivity. Current research has primarily focused on optimizing nitrogen use under existing climatic conditions, but there is a need to develop strategies that can adapt to changing environmental conditions, such as increased temperatures and altered precipitation patterns (Hou et al., 2021; Farooq et al., 2022).

Another critical research gap is the integration of new agronomic practices with genetic improvements. While there have been advances in identifying and manipulating genes associated with NUE, there is still a need for comprehensive studies that combine these genetic approaches with innovative agronomic practices, such as site-specific nutrient management and integrated nutrient management (Huang et al., 2018; Fiaz et al., 2021). Additionally, more research is needed to understand the interactions between different soil types and nitrogen dynamics, as these interactions can significantly affect NUE (Farooq et al., 2022). Future research should also focus on developing and testing new technologies, such as digital decision support tools and novel plant breeding techniques, to enhance NUE in diverse rice-growing environments (Chivenge et al., 2021; Fiaz et al., 2021).

8.3 Policy and sustainability frameworks

Government policies and international collaborations play a crucial role in promoting sustainable nitrogen management in rice farming. Effective policies can provide the necessary incentives and support for farmers to adopt NUE-enhancing practices. For instance, subsidies for precision farming equipment, slow-release fertilizers, and other NUE technologies can lower the financial barriers to adoption (Chivenge et al., 2021). Additionally, policies that promote education and training programs for farmers can help bridge the knowledge gap and encourage the use of sustainable practices (Xie et al., 2020).

International collaborations are also essential for sharing knowledge, resources, and technologies related to NUE. Collaborative efforts can lead to the development of standardized guidelines and best practices for nitrogen management, which can be adapted to local conditions (Chivenge et al., 2021). Furthermore, international research partnerships can facilitate the exchange of genetic materials and advanced breeding techniques, accelerating the development of high-NUE rice varieties (Fiaz et al., 2021). By aligning national policies with global sustainability goals, governments can create a supportive environment for the widespread adoption of NUE-enhancing practices, ultimately contributing to more sustainable and productive rice farming systems (Chivenge et al., 2021; Fiaz et al., 2021).

9 Conclusion

Enhancing nitrogen use efficiency (NUE) in rice is essential for sustainable agriculture, addressing the dual challenges of environmental degradation and economic inefficiency caused by excessive nitrogen (N) fertilization. Several strategies have been developed to improve NUE, focusing on genetic, agronomic, and technological innovations. Genetic approaches involve advances in molecular genetics and conventional breeding, aiming to develop rice varieties with enhanced NUE by targeting key traits related to N uptake, transport, and assimilation. Despite the complexity of these traits, technologies such as CRISPR/Cas9 offer promising avenues for precise genetic modifications. Agronomic practices, including balanced fertilization, the use of slow-release N fertilizers, split applications, and site-specific nutrient management (SSNM), have demonstrated effectiveness in improving NUE. Simplified nitrogen-reduced practices (SNRP) have further optimized N application and grain yield. Meanwhile, technological innovations like digital decision support tools (e.g., Rice Crop Manager and Nutrient Expert) have enabled precise N management by providing real-time field data, reducing N losses and improving efficiency.

Looking ahead, the future of sustainable rice farming lies in integrating these genetic, agronomic, and technological strategies. Research into the genetic basis of NUE will continue to be vital, with a focus on incorporating genes regulating N assimilation and remobilization into high-yielding rice varieties. Agronomic synergies, such as combining N-efficient rice varieties with SSNM and SNRP, will enhance both NUE and yield stability across diverse environmental conditions. Furthermore, advancements in digital tools and precision agriculture technologies will support real-time analytics and data-driven decision-making, ensuring efficient and sustainable N management. A holistic approach that merges genetic, agronomic, and technological innovations holds the potential to revolutionize rice farming, improving NUE while promoting environmental conservation and economic sustainability.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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