Harnessing Nitrogen Use Efficiency for Enhancing Productivity in Rice: A Review

ABSTRACT

Nitrogen fertilizers has significantly enhanced rice yields over the past decades, but it also had substantial negative effects on the environment. Excessive application of nutrients, particularly nitrogen, beyond crop requirements is linked to environmental losses. High nitrogen fertilizer input leads to low nitrogen use efficiency (NUE) due to the quick loss of nitrogen through ammonia volatilization, denitrification, surface runoff, and leaching in the soil-flood water system. Increasing the yield potential of rice based cropping systems in response to the global call for carbon neutrality is a crucial research target. New approaches are needed to boost yields while maintaining or ideally reducing nitrogen application to maximize crop NUE. Improving NUE is crucial for addressing the intertwined challenges of environmental degradation, climate change, and food security. This review provides an in-depth exploration of strategies for improving nitrogen use efficiency to enhance rice productivity while addressing agricultural and environmental challenges.

Keywords: Fertilizer, nitrogen, nitrogen use efficiency, rice

1. INTRODUCTION

Rice (*Oryza sativa* L.) acts as an essential dietary staple, providing sustenance to nearly half of the world's people [1].India occupies only 2.5% of the world's geographical area, yet it is home to approximately 18% of the global population. The rapid rise in the world's population is placing colossal demand to boost food productivity, placing immense pressure on the agricultural sector. The United Nations' world population index predicts that the global population will grow to 9.7 billion by 2050. By then, we need to produce 60 per cent more food on the same amount of land. To achieve food security, it is essential to guarantee a consistent supply of affordable, nutritious food - wherever people live. Mineral fertilizers are crucial for ensuring food security, with over half of the food consumed today resulting from their use. The cornerstone of global food production depends significantly on synthetic nitrogen fertilizers [2]. Among all plant nutrients, nitrogen (N) is the most critical and is a key factor limiting yields across different agro-ecological zones worldwide [3].Thus application of nitrogenous fertilizers is a crucial strategy to increase yields in intensive cropping systems.

Modern agricultural systems have consistently achieved significant yield increases, boosting grain supplies and avoiding widespread famine [4]. However, these systems have also led to global reactive nitrogen pollution exceeding a proposed planetary boundary, posing a high risk of adverse effects that could disrupt crucial Earth-system processes [5]. Global nitrogen fertilizer consumption has surpassed 200 million tons, with China using over 33% of the world's total annually. This makes China the leading country in fertilizer consumption worldwide [6]. Reactive nitrogen has been recognized as one of the top five emerging threats to humanity and the planet. Its effects on climate, environment, and public health are substantial, and this is closely connected to the global reliance on reactive nitrogen for food production [7].

The extensive application of fertilizers in agriculture has significantly disrupted the N cycle, resulting in a notable buildup of nitrates in soils and waters, as well as increased nitrogen oxides in the atmosphere. Crop plants utilize approximately 50 percent of the applied nitrogen fertilizer, while about 25 percent is lost from the soil-plant system due to leaching, volatilization, denitrification, and other factors. Farmers need to use large quantities of N fertilizer to agricultural crops because of its low recovery rate (30-50%), resulting from various losses within the soil-plant system [8]. Nitrogen lost from agriculture builds up in the surrounding environment, leading to air and water pollution, global climate change, and biodiversity loss[9]. These external impacts can be potentially very expensive for society [10]. Therefore agricultural systems that can address two vital societal needs are needed, i.e., high crop production and improved environmental quality.

Achieving high crop yields demands a substantial amount of plant-available nitrogen, but losses of inorganic nitrogen from agriculture are harmful to environmental quality[11, 12]. Losses of fertilizer nitrogen from agricultural systems are a significant concern for both farmers and environmentalists, as they not only lead to economic losses but can also cause pollution of groundwater, surface waters, and the atmosphere.

Environmental pollution can be reduced by tackling fertilizer overuse, enhancing NUE, and simultaneously maintaining or improving rice productivity and profitability. Thus NUE is an important economic and environmental goal [13].

The efficient use of nitrogen is a complex process influenced by a variety of soil, climate, and management factors. It requires a combined approach that considers agronomic, physiological, and molecular aspects. Among these, the agronomic approach is financially viable, environmentally sustainable, and practical. Sustainable agricultural production requires well-balanced, efficient, eco-friendly, and environmentally sound management practices.

Harnessing NUE is a critical strategy for enhancing productivity in rice (*Oryza sativa* L.), addressing both agricultural and environmental challenges. Here is an in-depth look at how this can be achieved:

2. IMPORTANCE OF NITROGEN IN AGRICULTURE

Nitrogen is the key nutrient vital for crop production. It forms the basic components of nearly all plant structures and is vital for chlorophyll, enzymes, and proteins. Nitrogen also plays a significant role in processes such as photosynthesis, leaf area production, leaf area duration, and net assimilation rate, all of which are closely connected to improving crop yield [14]. Nitrogen holds a distinct function as a plant nutrient because compared to the other essential nutrients, rather high amounts are required. It promotes root growth and crop development, as well as the absorption of other nutrients. As a result, plants excluding legumes that fix nitrogen (N□) from the atmosphere typically show a rapid response to nitrogen applications. Essentiality of N for plant growth was established in 1836 by Jean-Baptiste Boussingault, an agricultural scientist and chemist from Paris. In the late 1800s, Hellriegel and Wilfarth discovered that microbial communities have the ability to capture inert atmospheric nitrogen (N_2) and convert it into a usable form, a process known as biological nitrogen fixation [15]. N deficiency remains the most critical nutritional issue hindering crop yields globally. Therefore, efficient use of N in crop production is essential for enhancing crop yield and quality, ensuring environmental safety, and addressing economic factors[16]. It is projected that by 2050, global N fertilizer application will double to 300 million tonnes per year[17] and annual nitrogen losses from agricultural systems due to nitrate loss will reach 61.5 million tonnes[18].This will increase the risk of N loss from agricultural ecosystems and worsen environmental pollution issues.

3. IMPORTANCE OF NITROGEN IN RICE PRODUCTION

Nitrogen is the most crucial plant nutrient for positively boosting rice crop yields [19]. It is a crucial nutritional component for the productivity of cereal cropsand a significant factor that restricts agricultural yields [20]. However, traditional rice cultivation methods often lead to inefficient nitrogen use, with substantial amounts of applied nitrogen lost through leaching, volatilization, and denitrification. This not only reduces crop yield but also causes environmental issues. Optimal nitrogen management in rice cultivation is crucial for ensuring food security, addressing climate change, promoting adaptation and transformation, and achieving several sustainable development goals[21]. Though rice production consumes large quantities of nitrogenous fertilizers, only 20 to 50 per cent of it is taken up by the crop. NUE is generally low, with the worldwide average partial factor productivity (PFP) being 40 kg of grain per kg of nitrogen applied [22].

4. NITROGEN DEFICIENCY SYMPTOMS

Nitrogen is a nutrient that plants can readily transport throughout their tissues, so its deficiency initially manifests in the older leaves. In the early stages of growth, these leaves become pale and yellowish-green, and they turn increasingly yellow as the plant matures. N deficiency accelerated the senescence of older leaves. If a deficiency continues for an extended period, the older leaves of legumes may dry out and drop off. In instances of significant nitrogen deficiency, both the leaf area index and the leaf area duration decrease, resulting in reduced radiation interception, decreased radiation use efficiency, and lower photosynthetic rates. Plants exhibit stunted growth, yellowing leaves, diminished tillering in cereals, fewer pods in legumes, and ultimately, decreased yields in both cereals and legumes. N deficiency impairs both vegetative and reproductive growth in cotton, leading to premature senescence and potentially decreasing yield [23].

5. NITROGEN TOXICITY

Excess N causes delay in maturity and increases succulence. High N availability may alter the balance between vegetative and reproductive growth towards excessive vegetative growth. High nitrogen availability can shift the balance between vegetative and reproductive growth towards excessive vegetative growth. This can delay crop maturity and decrease lint yield in cotton[24]. It also causes lodging and abortion of flowers. Early maturity (approximately 5 days) was also observed in lowland rice plots that did not receive nitrogen, compared to those that received adequate nitrogen rates[25].

6. FACTORS INFLUENCING NITROGEN USE EFFICIENCY

NUE is intrinsically complicated, as each phase (including N uptake, translocation, assimilation, and remobilization) being influenced by various genetic and environmental factors. Numerous research studies have concentrated on optimizing crop management to enhance nitrogen efficiency by minimizing nitrogen losses and boosting nitrogen uptake. Reports indicated that the global average nitrogen use efficiency (NUE) was approximately 47% in 2009 and 42% in 2010, and the primary cause of the decline in NUE is the adoption of agronomic practices, such as nutrient management and the use of specific varieties, which are linked to low NUE[26].

7. NITROGEN UPTAKE AND PARTITIONING

To address the issues associated with nitrogen application in fields, it is crucial to understand the underlying mechanisms of NUE. The process of nitrogen (N) utilization in plants encompasses multiple stages. Initially, there is the primary phase of N uptake, followed by the reduction of nitrogen into usable forms. This is then followed by its assimilation into amino acids, translocation within the plant, and finally, the remobilization of nitrogen to the reproductive tissues.

Among essential plant nutrients, the uptake of nitrogen in crop plants is the highest. However, in certain cereal crops like rice, the uptake of nitrogen is second to that of potassium[27]. N is primarily taken up in the forms of NO_3^- and NH_4^+ by roots. In oxidized soils, nitrate (NO_3^-) is the primary form absorbed by plants. Conversely, in reduced soil conditions like those found in flooded rice fields, ammonium (NH_4^+) becomes the main form taken up. The topic of plant nutrition involving NH_4^+ versus NO_3^- has been thoroughly reviewed [28]. It has been demonstrated that most annual crops grow optimally when provided with mixtures of NH_4^+ and NO_3^- under controlled conditions.

8. EVALUATION OF NITROGEN USE EFFICIENCY

NUE is a well-established measure utilized to evaluate nitrogen management. Analyzing NUE provides insights into how plants respond to varying nitrogen availability. There are several formulas and definitions used to describe NUE. NUE is described as the dry mass productivity per unit N uptake from soil. It includes N absorption and utilization. NUE and N surplus are the most commonly used indicators for assessing the environmental performance of fertilization, which can be determined by

$$\text{NUE} = (N_{\text{uptake}} / N_{\text{fertilizer}}) \times 100$$

$$\text{N surplus} = \Sigma\,(N_{\text{inputs}}) - \Sigma\,(N_{\text{outputs}})$$

Where $N_{\text{uptake}}$and $N_{\text{fertilizer}}$ represent the amount of N uptake by the above-ground crop (kg-N ha^{-1}) and the applied N fertilizers (kg-N ha^{-1}), respectively. N_{inputs} (kg-N ha^{-1}) is the N inputs such as fertilization, atmospheric deposition, and irrigation water, and N_{outputs} (kg-N ha^{-1}) is the N losses such as plant uptake, atmospheric emissions, surface runoff and infiltration [29].

In 2007, Dobermann [30] reviewed the widely used indices for NUE in agricultural research, which include agronomy efficiency, recovery efficiency, internal efficiency, physiological efficiency and partial factor productivity.

NUE in rice, as outlined by Ladha et al. [31], encompasses diverse definitions and types utilized by researchers across various fields for specific objectives. Zheng et al.[32] propose a basic categorization of NUE, which hinges on the requirement of establishing an N-free plot during calculation. Additionally, NUE assessment typically involves three key indicators even when an N-free plot isn't established. They are (1) NUE for biomass production (NUE_B), which measures the dry matter (DM) produced by a unit of N absorbed by a crop, (2) internal NUE (IE_N), which evaluates the crop yield per unit of N absorbed, and (3) partial factor productivity of applied N fertilizer (PFP_N), an aggregate index which integratesN supply from the soil and N added from external sources. It typically decreases as the amount of N application increases. It is the ratio of grain yield to the N application rate. The initial two indicators, (NUE_B and IE_N), assess NUE by focusing on nitrogen uptake of plants, while PFPN highlights the straightforward relationship between grain yield and nitrogen application rate.

To assess NUE accurately when relying on the indigenous nitrogen supply of soil, it's essential to establish an N-free plot where the background nitrogen levels are accounted for. This category of NUE typically includes three key indicators: (1) recovery efficiency (REN), reflecting the percentage of applied nitrogen absorbed by plants; (2) physiological efficiency (PEN), showing how effectively absorbed fertilizer nitrogen translates into increased grain yield; and (3) agronomic efficiency (AEN), indicating the grain yield increase per unit of nitrogen fertilizer applied.

9. SOURCE OF NITROGEN FERTILIZERS

Before exploring the biochemistry and genetics associated with enhancing NUE in cereal crops, it's essential to grasp the emerging sources of nitrogen fertilizers, the varying impacts of nitrogen during different growth stages, the nitrogen levels within the crop, and the progress and efficiency of nitrogen utilization influenced by fertilizers. Global nitrogen fertilizer production relies on synthesizing atmospheric nitrogen into NH_3, which is then utilized in the creation of various inorganic fertilizers. These fertilizers may contain NH_4^+, NO_3^-, a blend of both, or the amide form ($-NH_2$). Additionally, compound fertilizers, comprising nitrogen along with other essential nutrients like phosphorus and/or potassium, are commonly employed. Various nitrogen sources are utilized, including anhydrous ammonia (82%N), urea (46%N), ammonium nitrate (34%), ammonium nitrate sulfate (26%), and aqua ammonia (25%N). Nitrogen fertilizers can generally be categorized as either organic or inorganic fertilizers. Firstly, regarding inorganic fertilizers, the majority of nitrogen, over 80%, comes from anhydrous ammonia application. Aqua ammonia, or ammonium hydroxide, is the second most important source of inorganic nitrogen fertilizers, with ammonia concentrations ranging from 25 to 29% by weight. Another form of nitrogen fertilizer is ammonium nitrate, which is significant agronomically as it combines two different forms of nitrogen (NH_4NO_3). Ammonium sulfate [$(NH_4)_2SO_4$] serves as a vital source of both nitrogen and sulfur, particularly beneficial for crops such as rice and in soils with high pH levels. Other fertilizers, like monoammonium [$NH_4H_2PO_4$], diammonium [$(NH_4)_2HPO_4$] phosphates, ammonium chloride (NH_4Cl), and ammonium sulfate, offer a dual nutrient composition, providing nitrogen, phosphorus, and chloride. Urea [$CO(NH_2)_2$] represents the organic form of fertilizer. The efficacy of inorganic fertilizers is governed by ion exchange principles. Due to its positive charge, NH_4^+-N is absorbed by negatively charged soil colloids (clay and organic matter), thus preventing leaching. Conversely, NO_3^--N, which carries a negative charge, is susceptible to leaching, particularly in sandy-textured soils. Most organic fertilizers originate from either plants or animals, often a combination of both. However, the majority is derived from the excrement and urine of livestock on farms, presenting in various forms such as farmyard or stable manure, urine, slurry, and compost.

10. STRATEGIES TO ENHANCE NITROGEN USE EFFICIENCY IN RICE

Enhancing NUE is advantageous for increasing crop yields, lowering production expenses, and preserving environmental quality. Yao et al.[33] suggested that reducing chemical fertilizer inputs could enhance NUE, lower N surplus, and reduce N -containing gas emissions without compromising crop yields.

10.1Soil Health Management

10.1.1 Soil Test-Based Fertilizer Application

Soil test-based (STB) fertilization leads to improved NUE. The STB approach is a key element of the 4R nutrient stewardship management principle: right source, right rate, right time, and right place. The 4R technique, as noted by Wang et al.[34] improves fertilizer efficiency, reduces nutrient losses, and mitigates environmental risks. It's widely acknowledged that effective nitrogen management in soil relies heavily on soil analysis, as highlighted by Nair[35]. This method yields several advantages across economic, agronomic, and environmental domains. The STB approach ensures precise fertilizer application, lowers production costs, boosts crop yield and quality, and minimizes nutrient runoff into water bodies and the atmosphere to a significant degree.Singh etal. [36] demonstrated that employing the STB method in rice cultivation not only increases productivity and profitability but also enhances NUE. Their study revealed that using STB fertilization resulted in a higher rice grain yield (4.2 t ha^{-1}) compared to both the standard recommended fertilizer dosage (3.75 t ha^{-1}) and the farmer's typical practice (3.18 t ha^{-1}).

10.1.2 Soil Chemistry Modification

Soil acidity is a significant barrier to crop production in many regions worldwide. Soils tend to become more acidic over geological time, particularly in areas with high rainfall, because bases are washed down to deeper layers, leaving the surface soil more acidic. Acidity is associated with the release of protons (H^+) during the processes of C, N, and S transformation and cycling within soil-plant systems [37]. Plant growth on acidic soils can be hindered by nutrient deficiencies such as N, P, K, Ca, Mg, or Mo. Additionally, toxic levels of H, Al, or Mn, slower decomposition of organic matter, impaired nutrient cycling by microflora, and decreased nutrient uptake and root growth inhibition can also pose challenges [38].

In submerged rice fields, fertilizers that produce ammonia, such as urea, are most effective because ammonia remains the most stable N form under these conditions. For acidic upland soils, ammoniacal fertilizers are best suited for the rainy season because ammonium binds to soil particles, thereby minimizing leaching losses. This bonded ammonium is gradually converted to nitrate, providing a sustained supply of nutrients for crops. In very acidic upland soils, urea is preferred over ammonium sulfate since it generates less acidity. In contrast, in alkaline upland soils located in areas with low rainfall, nitrate fertilizers are preferred over ammoniacal fertilizers or urea due to the risk of ammonia loss through volatilization under alkaline conditions.

10.1.3 Integrated Nutrient Management

Integrated nutrient management is a systematic approach that equally prioritizes all components, including generating resources on-site, utilizing off-site nutrient resources, and effectively integrating and managing these resources [39]. The promotion of organic nutrition is hindered by poor availability, imbalanced and inconsistent nutrient content, and the high cost of transportation. Thus the conjunctive use of chemical fertilizers and organic materials for soil fertility management is considered as an option to come out of the 'vicious spiral' of agrochemical menace. Combining organic and inorganic fertilizers aids in nutrient conservation, allows for a slower nutrient release, and improves the soil's physical, chemical, and biological characteristics. Nonetheless, variations in the amounts and ratios of N, P and K can reduce the effectiveness of organic manures. Therefore, the key challenge lies in effectively combining organic manures of varying qualities with chemical fertilizers to maximize nutrient accessibility. The combined use of organics inorganics accelerated growth components more effectively than the application of inorganic fertilizers alone. The growth was greater with NPK + FYM compared to 100 percent NPK. According to Ganapathy et al.[40], using organic manures alongside inorganic fertilizers was more beneficial for rice growth compared to using only inorganic fertilizers. The partial factor productivity of nitrogen (PFPN) in rice varied from 26 to 52 kilograms of grain per kilogram of nitrogen when applying the recommended dose of NPK fertilizers. However, this figure rose to 33–77 kilograms of grain per kilogram of nitrogen when using 75% of the recommended dose of NPK combined with 25% nitrogen from farmyard manure[41]. Panda et al.[42] found that the highest yields were obtained with a combination of NPK fertilizers and FYM. They concluded that the best approach for maximizing and sustaining rice yields, as well as improving soil health, involves a balanced application of N, P and K fertilizers along with FYM.

10.2 Optimized Fertilizer Application

10.2.1 Split Application

Application of N fertilizers in split doses during the growing season can help improve NUE and reduce losses. Over 60% of applied nitrogen (N) is lost because the supply does not align with the crop's demand [43]. Due to the favorable conditions for nitrogen loss in rice cultivation, it has been recommended to apply nitrogen in multiple split doses to improve its utilization efficiency. Farmers typically follow a particular schedule for applying nitrogen fertilizer, commonly adhering to the recommended split ratios of 1:2:1 or 2:1:1 at the basal, maximum tillering, and panicle initiation stages. However, this approach doesn't consider whether the plant truly needs nitrogen at those specific times, potentially resulting in nitrogen loss or insufficient synchronization between nitrogen supply and the actual nitrogen requirement for crops [44].

A recommended strategy to maximize efficiency is to apply nitrogen fertilizer close to the crop's uptake requirement timing. Studies have shown that applying the full dose of nitrogen fertilizer at the beginning increases nitrogen losses through volatilization, leading to lower NUE [45]. Conversely, splitting the nitrogen application ensures that the nutrient is available according to the crop's demand throughout the growing season. Research suggests that dividing nitrogen application into three stages—planting, tillering, and panicle initiation—results in higher yields and improved NUE in rice. Kaushal et al. [46] found that adopting this approach enhances grain yield significantly in modern rice varieties.

10.2.2 Site Specific Nutrient Management (SSNM)

Site-specific nitrogen management is an approach aimed at providing rice with nutrients as required, accounting for field-specific variations in soil nitrogen levels. Unlike many fertilizer management methods, which overlook these variations and can lead to excessive nitrogen application and reduced NUE, SSNM considers various factors such as crop nutrient demand, desired yield, climate conditions, soil nitrogen supply, irrigation water, and organic material mineralization [42]. Determining the availability of indigenous nitrogen sources specific to each site is crucial, as it varies across locations. Consequently, nitrogen recommendations vary accordingly. Implementing site-specific nitrogen management in rice has shown a significant reduction in total nitrogen application by 25%, leading to improved fertilizer NUE compared to conventional farmer practices [47].

10.2.3 Use of Controlled-Release Fertilizers

Controlled-release fertilizers (CRFs) effectively deliver nutrients to plants over a prolonged duration, releasing them gradually. Unlike conventional fertilizers that dissolve quickly after application and require multiple doses, CRFs reduce nutrient loss to the environment and improve nutrient utilization efficiency. Aligning the nutrient release of CRFs with crop needs promotes optimal growth while reducing nutrient leaching, volatilization, denitrification, and runoff. Additionally, CRFs have the potential to maintain or boost crop yields with reduced overall nutrient inputs, offering a significant alternative in areas where nitrogen inputs are restricted.

The advancement in controlled-release urea (CRU) application offers the potential for increased crop yields and NUE. CRU mitigate N loss by addressing processes like surface runoff, ammonia volatilization, leaching, and nitrous oxide emission [48]. CRFs aid in minimizing nitrogen loss by using slow-release fertilizers, ensuring a consistent nitrogen supply over time. They are typically coated with various natural or synthetic substances like resin, paraffin, polychlorovinyl, polyurethane, sulfur, polylactic acid, natural rubber, and neem [48]. Regarding advanced or organic fertilizers, the utilization of CRFs can enhance NUE by 30.7–44.0 per cent [49]. These substances mitigate nitrogen losses by virtue of their ability to delay nitrogen release, thus potentially enhancing the alignment between crop demand and soil nitrogen supply. Neem coated urea (NCU) is widely used as a slow-release nitrogen fertilizer in India. According to Chen et al.[50] the application of CRU, like resin-coated and polyurethane-coated urea, led to significant increases in nitrogen agronomic efficiency (AEN) and PFP of N by 17.4-52.6% and 23.4-29.8% respectively, compared to conventional urea application in rice cultivation. Similarly, Sireesha et al. [51] found that using 100% NCU resulted in a higher NUE of 32.59% compared to 20.68% with 100% prilled urea. Furthermore, in lowland rice cultivation, the application of 100% NCU led to a 14% increase in grain yield compared to 100% prilled urea.

10.2.4 Deep Placement of Fertilizers

This involves placing ammoniacal N fertilizers in the soil's reduction zone, principally in paddy fields, ensuring that ammoniacal N remains accessible to the crop. This method ensures more effective fertilizer distribution in the root zone soil and reduces nutrient loss due to runoff and ammonia volatilization. It is widely recognized that deep placement of fertilizers is essential for enhancing nutrient use efficiency (NUE). Yanhui et al.[52] revealed that in rice paddies, deep fertilization could reduce nitrogen loss by 20.9–24.8% directly through decreased ammonia (NH_3) volatilization and denitrification losses, and indirectly by influencing periphytic biofilm development. Although periphytic biofilm development can increase nitrification-denitrification loss, it reduces NH_3 volatilization loss, leading to an overall increase in N loss by 3.1–7.1% [52]. Li et al.[53] suggested that for mechanical direct-seeded farms, one-time deep placement could effectively enhance both grain yield and NUE, and thus lower GHG emissions. Liu et al.[54] found that placing N fertilizer deeply at a 10 cm soil depth significantly improved NUE and rice grain yield, as it reduced the average concentration of NH_4^+-N in floodwater compared to the traditional method of broadcasting N fertilizer.Recent research has indicated that placing urea deeply in rice fields can reduce ammonia (NH_3) volatilization losses by 91% [55] and decrease N_2O emissions by 8–46% compared to surface broadcasting.

10.2.5 Precision Farming

Applying nitrogen fertilizers at optimal times and rates to align with the crop's growth stages and nitrogen requirements is crucial. Precision agriculture is defined as an integrated, technology-based agricultural management system designed to address the variation across different locations and over time in every aspects of agricultural production, aiming maximum profitability, sustainability, and environmental protection [56]. The focus of precision agriculture is to enhance nutrient use efficiency by, necessitating (i) suitable decision support systems and (ii) equipment that can adjust application rates to different scales as needed. Aligning fertilizer applications with the unique conditions of each field requires assessing and comprehending the variability in soil properties and nutrient levels, and understanding how these factors influence crop performance.

10.3 Crop Management Practices

10.3.1 Water management

Effective water management is essential for controlling the soil's redox potential, which influences how nutrients move and are available in the soil, ultimately affecting their uptake by crops [57]. Techniques such as alternate wetting and drying (AWD), mid-season drainage, controlled irrigation, and intermittent irrigation are employed to improve water use efficiency, reduce greenhouse gas emissions, and enhance nitrogen (N) recovery without compromising rice yields [58]. In comparison to continuous standing water irrigation, AWD increases the AEN, PFP, and apparent recovery efficiency of N by 6.1%, 5.7%, and 5.1% in 2010, and by 8.9%, 6.9%, and 6.1% in 2011, respectively, in rice [59]. The improved NUE in water-saving management practices may be attributed to their ability to ensure adequate oxygen supply to rice roots, which enhances soil organic matter mineralization and reduces nitrogen immobilization, thus making nutrients more available for plant uptake [60].

10.3.2 Crop Rotation

Improving NUE can be achieved by increasing soil organic N reserves and boosting internal nitrogen recycling through the use of crop rotations. Complexity of crop rotation refers to the variety and sequence of crops grown over time, including both cash and cover crops. Incorporating a greater variety of crops in rotation enhances plant functional diversity and is known to boost crop yield [61]. Increasing crop diversity can improve the cycling of organic nitrogen in agroecosystems, potentially lowering the need for excessive fertilizer use [62, 63].

Pillai et al.[64] studied the balance-sheet of available N (kg ha^{-1}) in soil as influenced by cropping sequence and nutrient management and reported that the crop sequence of rice-rice-sesame and rice-rice-okra showed a loss in the soil N after 2 years of study. On the contrary, the rice-rice-groundnut and the rice-rice-cowpea crop sequences were found to enhance the soil-N status. The gain in the available N was 72.19 kg ha^{-1} and 48.32 kg ha^{-1} during the first year and 20 86.65 kg ha^{-1} and 22.70 kg ha^{-1} after the second year for the rice-rice-groundnut and rice-rice cowpea sequences respectively. Legumes impose less demand on soil resources and simultaneously have the ability to fix atmospheric N in their root nodules. The yield of rice succeeding cowpea and groundnut increased, whereas of that which followed sesame decreased.

10.3.3 Conservation Agriculture

Conservation agriculture, a farming method, offers benefits like increased crop productivity, soil enhancement, and environmental sustainability. It operates on three core principles: minimal disturbance to the soil, continuous soil cover with mulch, and crop diversification, incorporating legumes and cover crops, alongside other effective farming and land management techniques. Alam et al.[65] found that conservation agriculture methods in rice-based cropping systems boosted the storage and accessibility of soil nitrogen (N) for crops. For instance, strip planting and transplanting seedlings without puddling the soil, coupled with high residue retention, increased total N levels significantly compared to conventional tillage methods. This increase is likely due to reduced soil disturbance, which helps in retaining N in organic and inorganic forms by regulating decomposition and loss processes.

Similarly, Salahin et al.[66] carried out a field study to assess the impact of tillage methods and crop residue retention on nitrogen cycling. After three years, they observed that increased residue led to higher total nitrogen (TN) levels across different soil depths compared to initial nitrogen stocks. Zero tillage, strip tillage, and bed planting methods also sequestered more TN compared to conventional practices, especially at shallow soil depths. Strip tillage, in particular, showed the highest TN sequestration, especially when combined with significant residue retention. This effect may be attributed to reduced nitrogen mineralization in the soil, especially with increased residue retention, as decay rates of potentially mineralizable nitrogen were lower under strip tillage with residue retention.

10.4 Physiological and Morphological Approaches

10.4.1 Root Architecture:

Developing varieties with deeper and more extensive root systems is crucial for optimizing nitrogen uptake efficiency from the soil. The structure and function of rice roots have a significant impact on nitrogen uptake and utilization, directly influencing NUE [67]. These characteristics play a pivotal role in maximizing nitrogen absorption and minimizing nitrogen leaching into groundwater and deeper soil layers. Improving root development, the ratio of roots to shoots, and root architecture are recognized as key factors in enhancing NUE [68, 69]. Enhancing root system traits and leaf area while maintaining a balanced source-sink relationship are crucial physiological factors for maximizing yield and NUE in nitrogen-efficient crop varieties. Under low nitrogen conditions, root growth tends to be stimulated, whereas it is suppressed under high nitrogen conditions, as indicated by Xin et al. [70]. Yan et al. [71] demonstrated that augmented root biomass and length correlate with improved grain yield, crop water productivity, and various NUE parameters.

Creating a resilient root system architecture that integrates various root traits such as nodal root distribution, root hair characteristics, length and density, as well as branching patterns, thickness, and volume, could effectively address the challenge of optimizing nutrient absorption, particularly nitrogen uptake. Diverse root traits play critical roles in nutrient assimilation across various stages of crop growth and maturation.

10.4.2 Enhanced Photosynthesis:

NUE is intricately tied to a crop's ability to absorb nitrogen and produce materials. The photosynthetic capability of crops forms the foundation for producing materials, which subsequently dictates yield levels and NUE [72].Hence, selecting traits that boost photosynthetic efficiency is crucial for enhancing nitrogen assimilation and plant growth, thereby achieving a synergistic effect of high yield and NUE. Two key elements influencing the photosynthesis and nitrogen use in plant leaves are the net photosynthetic rate (Pn) and photosynthetic nitrogen use efficiency (PNUE). PNUE represents the ratio of Pn to the nitrogen content per unit leaf area (NA), indicating the leaf's nitrogen utilization capacity and the influence of leaf nitrogen on photosynthesis [73]. This parameter is crucial for evaluating the potential yield enhancement in wheat cultivar improvements.

Richards [74] states that higher crop yields have been attained through enhanced or prolonged photosynthesis per unit of land and increased allocation of crop biomass to the harvested yield. These improvements have primarily resulted from the implementation of irrigation systems, advancements in agronomic techniques- especially the adoption of synthetic fertilizers and higher concentrations of atmospheric CO_2. Meanwhile, the increase in biomass allocation to harvested products is predominantly attributed to advancements in plant breeding techniques.

10.5Exploiting Symbiotic Relationships

10.5.1 Biological Nitrogen Fixation:

Biological nitrogen fixation (BNF) is the process where atmospheric nitrogen is transformed into ammonia by nitrogenase enzymes, performed by specific prokaryotes known as diazotrophs, belonging to Archaea and Bacteria domains. Understanding the genetics of BNF in detail can accelerate the optimization of nitrogenase function and regulation, improve the associations between diazotrophs and plants, and facilitate the transfer of nitrogen-fixation genes to cereal crops [75]. Exploring and harnessing symbiotic relationships with nitrogen-fixing bacteria can naturally enhance nitrogen availability. Incorporating legume crops into any agricultural system leads to a reduction in synthetic fertilizer, water, and associated energy usage, while enhancing soil fertility [76]. Legumes have the capability to fix atmospheric nitrogen, forming associations with symbiotic bacteria like Rhizobium. BNF not only benefits existing crops but also reduces the nitrogen needs of subsequent non-leguminous crops. Including legume crops in rice-based agricultural systems may effectively increase rice yield and nitrogen content in rice, while decreasing nitrogen loss from the soil [77].

10.5.2 Endophytic Bacteria:

Exploring the use of beneficial endophytic bacteria that live within the rice plant and help in nitrogen fixation and assimilation. These bacteria form beneficial interactions between plant roots, enhancing nutrient availability, fostering plant growth, and combating soil-borne pathogens. The most extensively studied aspect of plant growth-promoting bacteria is their ability to enhance nutrient acquisition for plants, such as nitrogen, iron, and phosphorus, rendering them readily available [78]. Certain endophytic bacteria have the capacity to convert atmospheric nitrogen into a usable form for plants through nitrogenase activity. Khan et al. [79] demonstrated that using *Burkholderia sp.* (isolate BRRh-4) and *Pseudomonas aeruginosa* (isolate BRRh-5) alongside half the usual amount of NPK fertilizers boosted rice grain yield by 5% and 17%, respectively, compared to using the full recommended dose of NPK fertilizers.

10.5.3 Biofertilizers for boosting fertility

Biofertilizers, also known as microbial inoculants or bioinoculants, are formulations containing living microorganisms beneficial for agriculture, aiding in nitrogen fixation, phosphorus solubilization, or nutrient mobilization, ultimately boosting soil and crop productivity (Fertilizer Control Order, 1985). They do not directly supply nutrients to plants but facilitate efficient nutrient utilization, including nitrogen, phosphorus, potassium, and micronutrients, along with antibiotics, hormones, and vitamins. Bio-fertilizers are preparations containing beneficial microorganisms that enhance microbial activity, which in turn increases the mobilization and solubilization of soil nutrients, either directly or indirectly [80].

Nitrogen-fixing biofertilizers consist of microbial inoculants or groups of microorganisms that can convert atmospheric nitrogen into a usable form. Conversion of atmospheric nitrogen to ammonia is catalyzed by the enzyme nitrogenase. Malo and Sarkar [81] investigated the impact of inorganic and bio-fertilizers on rice in the New Alluvial Zone of West Bengal. They found that treatments T4 (75% recommended dose of NP + 100% RDK + *Azotobacter chroococcum*) and T5 (75% recommended dose of NP + 100% RDK + *Bacillus polymyxa*) significantly improved soil health. This improvement was reflected in increased organic carbon content, available N, P_2O_5 and K_2O. Consequently, these treatments positively impacted soil health, nutrient use efficiency, and led to higher rice yields, soil conservation, and sustainability.

10.6 Genetic Approaches

10.6.1 Traditional Breeding:

Utilizing traditional landrace varieties that naturally exhibit higher NUE. Numerous studies have demonstrated that there is genetic variation for NUE in rice [82], suggesting that selecting different genotypes could enhance NUE in rice. Rice landraces, which include indigenous and locally grown varieties maintained by traditional farmers, may offer substantial genetic diversity that can be utilized to improve the NUE of cultivated rice varieties.

10.6.2 Molecular Breeding:

Incorporating molecular techniques like genomics and marker-assisted breeding into conventional breeding programs has transformed the improvement of complex traits in crops[83]. These advancements have enabled breeders to precisely identify and select desirable traits at the molecular level, improving efficiency and effectiveness in crop improvement. By leveraging genomics, researchers can now map and manipulate genes associated with optimal NUE traits, yield, disease resistance, and stress tolerance more accurately. Marker-assisted breeding further streamlines the process by using specific DNA markers linked to target traits, expediting the development of superior crop varieties and ultimately contributing to enhanced agricultural productivity and sustainability.

10.6.3 Genetic Engineering:

To improve nitrogen use efficiency (NUE) and crop productivity, strategies have largely centered on genetic modification, specifically targeting genes involved in nitrogen uptake, distribution, metabolism, and regulation [84]. For instance, enhancing the expression of the nitrate transporter gene OsNRT1.1A/OsNPF6.3 has been shown to improve nitrogen utilization, increase grain yield, and shorten maturation time [85]. Additionally, transgenic plants overexpressing OsAMT1;1 exhibit significantly higher nitrogen uptake, which results in better plant growth and increased grain yield, particularly in environments with low NH_4^+ availability [86]. A transgenic method could be employed to genetically modify plants by focusing on particular genes linked to NUE. That is, introducing genes from other organisms that confer better nitrogen utilization capabilities.

10.3.4 Genotype Selection

Choosing genotypes with better NUE is a strategy for optimizing resources. Most rice farmers achieve less than 60 per cent of the genetic yield potential of high-yielding rice varieties [87] due to various factors including low NUE. The study conducted by Ju et al. [88] revealed that that rice varieties with high NUE produced significantly greater yields and NUE compared to those with low NUE when nitrogen (N) was applied at moderate or low rates. Choosing high-yielding rice varieties with greater NUE at lower nitrogen input levels is a key strategy for cost-effectiveness [89]. Karmakar et al. [90] observed that increasing N rates led to a reduction in NUE, demonstrating a negative correlation between NUE and nitrogen application rates.

All improved rice varieties have been bred and developed under ideal conditions, which include high input levels and optimal management practices. Response of varieties to suboptimal doses of nitrogen is indicative of their NUE [88]. Thus identification of N efficient varieties combined with scientific agronomic management is a prospective approach for enhancing NUE of rice.

Although various approaches aimed at sustainable agriculture have been shown to enhance NUE, nitrogen responsiveness is suggested as a more suitable trait for selecting varieties with lower N requirements[91].

11. CONCLUSION

Nitrogen is a crucial nutrient that limits crop yields across different agro-ecological regions. The dynamic characteristics of nitrogen and its tendency to be lost from soil and plant systems present a unique and difficult context formanaging it effectively. N recovery by crops grown under most cropping systems is below 50%. This low recovery is linked to N losses due to NO_3leaching, NH_3 volatilization, surface runoff, and denitrification. To address the increasing demand for nitrogen fertilizers driven by the rising food demands of a growing population while also tackling environmental and atmospheric pollution, enhancing NUE seems to be a feasible remedy. While nitrogen fertilization is vital for food production, optimizing its management is highly complex.

Enhancing NUE in rice is a multifaceted approach that involves better agronomic practices, genetic improvement, and exploiting symbiotic relationships. By integrating these strategies, it is possible to achieve higher rice productivity while minimizing environmental impact. Continuous research, collaboration, and field validation are essential to harness the full potential of NUE in rice cultivation.

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