

Review Article

ROLE OF NITROGEN IN WHEAT PRODUCTION SYSTEM AND NITROGEN FOR IMPROVING WHEAT YIELD AND QUALITY: A REVIEW

Abstract

Wheat is the staple food across the different parts of the world. To increase the wheat productivity by utilizing the fertilizers. Nitrogen plays a key role in increasing productivity and the quality of the crops. In this review article, we studied the relationship between nitrogen and wheat parameters, the impact of excessive nitrogen used in wheat, NUE (Nitrogen use efficiency) in wheat production, and examined various nitrogen management strategies aimed at enhancing both yield and quality. Different nitrogen application techniques, such as broadcast and side-dressing, have been evaluated, with the rate of nitrogen showing a significant influence on wheat parameters. Key components influencing NUE in wheat farming, including soil characteristics, nitrogen application timing and rate, environmental factors, and crop genetics, are discussed. Furthermore, innovative nitrogen management practices such as precision farming techniques, cover cropping, and the use of biofertilizers as effective strategies for improving NUE and promoting sustainable wheat production. The abstract underscores the importance of balancing nitrogen application to meet crop demands at different growth stages while minimizing nitrogen losses and environmental risks. By integrating advanced technologies, agronomic practices, and scientific insights, farmers can optimize nitrogen use efficiency in wheat production systems, thereby enhancing both yield and quality outcomes.

Keywords: Nitrogen Use Efficiency (NUE), Wheat Production, Nitrogen Management, Yield Improvement, Quality Enhancement

Introduction:

Wheat is a cornerstone of global food security and is cultivated in 89 countries to feed around 2.5 billion people one-fifth of the total world population. It belongs to the family Poaceae, tribe Triticeae, and is considered to be the first ever domesticated crop. (Mastrangelo & Cattivelli, 2021). India has witnessed a significant transformation in its agricultural sector over the past few decades, with wheat playing a crucial role in the nation's food security and economy [91,92,93,94]. The country ranks second globally in wheat production, accounting for approximately 14% of the world's wheat output (Madhukar *et al.*, 2021). Notably, the state of Haryana has shown a positive growth rate in wheat production, particularly from 1980 to 1989, and is recognized for its wheat yield sustainability, ranking second after Punjab (Devi *et al.*, 2021).

In the upcoming century, climate changes are predicted to occur that will create problems for food security and crop production. As the world grapples with escalating food demands, understanding the nuances of wheat cultivation (Gupta *et al.*, 2023). The need of the time is to increase the productivity of arable land by utilizing fertilizer supplies for crop cultivation. The application of fertilizers (NPK) is essential to restore the soil nutrients and to reduce the yield gap particularly the role of nitrogen (N), which becomes paramount (Salim & Raza, 2020). Nitrogen, an essential nutrient in plant biology, enhances photosynthetic capacity, growth rates, and seed production, directly influencing wheat yield and quality (Jensen *et al.*, 2020).

Nitrogen (N) is a critical macronutrient for cereal crops, playing a pivotal role in plant growth, development, and yield (Fortunato *et al.*, 2023). It is a key component of amino acids, proteins, chlorophyll, and nucleic acids, which are essential for plant cellular functions and metabolism (Zuluaga & Sonnante, 2019). Nitrogen use efficiency (NUE) is a measure of how effectively plants utilize available nitrogen, and it is a significant factor in agricultural sustainability and productivity (Bharati & Mandal, 2020). Nitrogen use efficiency (NUE) is a crucial metric in agriculture that measures the effectiveness of nitrogen utilization in crop production. It involves understanding the relationship between the total nitrogen input and the nitrogen output, focusing on factors like uptake, metabolism, and redistribution of nitrogen within plants. NUE calculations typically consider the ratio of nitrogen output (e.g., grain yield) to nitrogen input (e.g., nitrogen supply from soil, organic manure, and inorganic applications). Achieving high NUE is essential for improving efficiency, profitability, and sustainability in farming practices (Congreves *et al.*, 2021).

The effect of nitrogen use efficiency (NUE) on wheat production is multifaceted, with studies demonstrating that improved NUE can lead to increased wheat yields and sustainability in agricultural systems. Efficient nitrogen management practices, such as precision fertilization and integration with organic amendments, have been shown to enhance wheat yields and NUE parameters (Li *et al.*, 2022; Rehim *et al.*, 2020). Additionally, varietal differences in wheat also influence NUE, with certain varieties exhibiting higher N uptake and utilization efficiencies under varying nitrogen supply conditions (Singh & Arora, 2001).

This review aims to synthesize existing literature on wheat cultivation with a focus on optimizing nitrogen use. We will explore mechanisms through which nitrogen efficiency can be enhanced in wheat production, assess the environmental impacts of nitrogen overuse, and discuss sustainable practices that could mitigate adverse outcomes. By integrating findings from key studies (e.g., Jensen *et al.*, 2020; Wezel *et al.*, 2014; Steffen *et al.*, 2015), this paper will contribute to a nuanced understanding of nitrogen's dual role as both a vital nutrient and an environmental challenge in the context of modern agriculture.

Relationship between Nitrogen Application and wheat characteristics

The relationship between nitrogen (N) application and wheat characteristics is multifaceted, with studies demonstrating that appropriate N fertilization can significantly enhance wheat growth, yield, and nutrient uptake. Controlled-release nitrogen fertilizers (CRNF), such as polymer-coated urea (PCU) and sulfur-coated urea (SCU), have been shown to synchronize nitrogen release with the wheat's nitrogen demand, improving nitrogen use efficiency (NUE) and grain yield when applied twice, at pre-sowing and re-greening stages (Ma *et al.*, 2021). Additionally, nitrogen application rates and water quality under water-limited conditions have been found to affect yield productivity and plant growth, with optimal ratios of low-quality water (LQW) and high-quality water (HQW) not significantly decreasing yield when nitrogen is adequately applied (Mahdy *et al.*, 2022).

Different nitrogen application techniques, such as broadcast and side-dressing, have been evaluated, with the rate of nitrogen showing a significant influence on wheat parameters, particularly at higher doses up to 180 kg N/ha (Ullah *et al.*, 2013). Moreover, crop residue management practices combined with nitrogen levels have been observed to increase wheat growth

and yield attributes, with the application of 120 kg N/ha yielding the highest growth and nutrient uptake (Shah *et al.*, 2015). The interactive effects of tillage and nitrogen fertilization methods have also been studied, revealing that no-tillage combined with nitrogen fertilization significantly increases soil quality attributes and wheat productivity (Yuan *et al.*, 2022).

Sensor-based nitrogen application has been shown to improve plant height and tiller density in wheat crops (Patel *et al.*, 2024), while a rational application of nitrogen fertilizers, including a reduction in N fertilizer dose and replacement with organic manure, has been found to maintain crop yield and enhance soil biological properties without significant changes in N uptake (Guan *et al.*, 2011). However, nitrogen fertilization can also increase the uptake of undesirable elements such as cadmium (Cd) in wheat, indicating a need for careful management of N application rates (Mitchell *et al.*, 2000). Furthermore, the interaction between seed rate and nitrogen fertilization has been studied, with optimal rates of both factors leading to the highest yield and growth parameters in wheat (Sarker *et al.*, 2022). Lastly, potassium fertilization has been shown to influence the accumulation of macronutrients in wheat, including nitrogen, suggesting that nutrient management should consider the combined effects of multiple fertilizers (Kubar, 2018).

Impact of Nitrogen on wheat yield:

Increased nitrogen levels, coupled with higher crop densities, were found to suppress weed biomass and improve wheat competitiveness, leading to increased grain yield and spikes per square meter (Banisaeidi *et al.*, 2014), optimal nitrogen rates were associated with increased yields in different tillage practices (Feng *et al.*, 2014) and genotypic responses to nitrogen application also showed marked significance in yield optimization (Hnizil *et al.*, 2024). However, excessive nitrogen can lead to increased susceptibility to diseases such as powdery mildew and stripe rust, which negatively correlate with yield (Luo *et al.*, 2021). Contradictions arise when considering the environmental impact and efficiency of nitrogen use. While higher nitrogen levels generally correlate with increased yield (Bibi *et al.*, 2016), there is a point beyond which no further yield benefits are observed and may even negatively impact nitrogen use efficiency (NUE) and grain quality (Boulelouah *et al.*, 2022). Moreover, excessive nitrogen fertilization contributes to greenhouse gas emissions, although certain management strategies can mitigate these effects while maintaining yield benefits (Guo *et al.*, 2022). In conclusion, nitrogen fertilization is a critical factor in optimizing wheat yield, with studies

indicating that yields improve with increased nitrogen application up to a certain threshold (Banisaeidi *et al.*, 2014; Hnizil *et al.*, 2024; Ullah *et al.*, 2013). However, the relationship between nitrogen and yield is complex, influenced by factors such as crop density, tillage practices, genotype, and disease pressure (Banisaeidi *et al.*, 2014; Hnizil *et al.*, 2024; Luo *et al.*, 2021). Additionally, the environmental impact and efficiency of nitrogen use must be considered, as excessive nitrogen can lead to diminished returns and increased environmental costs (Guo *et al.*, 2022). Therefore, a balanced approach to nitrogen fertilization, tailored to specific conditions and wheat varieties, is essential for sustainable wheat production (Hnizil *et al.*, 2024; Sun *et al.*, 2018; Yin *et al.*, 2022).

NUE in wheat production:

Nitrogen use efficiency (NUE) in wheat production is a critical factor for optimizing grain yield and quality while minimizing environmental impacts. Studies have shown significant genetic variability in NUE among wheat cultivars, with some genotypes demonstrating superior efficiency in utilizing applied nitrogen (Aga *et al.*, 2024; Silva *et al.*, 2014; Todeschini *et al.*, 2016). Nitrogen remobilization efficiency (NRE) and nitrogen utilization efficiency (NUtE) are key components of NUE, with NRE playing a dominant role in cultivars under both low and high nitrogen conditions (Todeschini *et al.*, 2016). Additionally, NU_pE and NU_tE are important traits contributing to NUE, with efficient genotypes showing stability across environments (Aga *et al.*, 2024).

Contradictory findings suggest that while NUE generally increases under low nitrogen conditions, certain traits such as NU_tE may decrease as nitrogen supply is increased, stabilizing at a certain threshold (Aga *et al.*, 2024; Todeschini *et al.*, 2016). Moreover, the relationship between nitrogen accumulation, transport, and yield indicates that improving NUE for grain and biomass production is essential under both irrigated and rainfed conditions (Jinwen *et al.*, 2019). Interestingly, tall wheat varieties have shown higher N uptake and NUE for dry matter production, whereas dwarf cultivars excel in NUE for grain production (Singh & Arora, 2001). In conclusion, enhancing NUE in wheat production involves selecting genotypes with improved NUE traits, particularly under low nitrogen conditions. The identification of genotypes with high NUE is crucial for sustainable wheat production, as it can lead to stable yields across varying environmental conditions and reduce the need for excessive nitrogen fertilization (Aga *et al.*,

2024; Silva *et al.*, 2014; Jinwen *et al.*, 2019). Future research should focus on the genetic basis of NUE and the development of breeding strategies that incorporate NUE-related traits to improve wheat cultivars (Guttieri *et al.*, 2017).

Loss of nitrogen use efficiency in wheat:

Nitrogen use efficiency (NUE) in wheat crops is influenced by various pathways through which nitrogen can be lost, including volatilization, leaching, denitrification, and surface runoff (Govindasamy *et al.*, 2023). Gaseous nitrogen loss from wheat plants has been identified, particularly between anthesis and post-anthesis stages, with significant losses occurring in this period (Kanampiu *et al.*, 1997). Additionally, the study of winter wheat systems revealed that NUE is higher when wheat is harvested for forage before anthesis, as opposed to grain, due to the avoidance of large nitrogen losses after flowering (Thomason *et al.*, 2000).

Interestingly, while the physiological and molecular mechanisms underlying NUE are being unraveled, such as the identification of differentially expressed genes (DEGs) related to carbon and nitrogen metabolism in wheat genotypes with contrasting NUE (Zhang *et al.*, 2021), the translation of scientific knowledge into farm practice remains limited (Whetton *et al.*, 2022). Moreover, spatial and temporal variations in NUE have been observed, with state-level NUE in winter wheat showing an increasing trend in recent decades, potentially reducing nitrogen loss from agricultural production (Lu *et al.*, 2019).

In summary, NUE losses in wheat crops are primarily due to nitrogen volatilization, leaching, and denitrification, with significant losses occurring after the anthesis stage (Govindasamy *et al.*, 2023; Kanampiu *et al.*, 1997). While molecular insights are providing a deeper understanding of NUE (Zhang *et al.*, 2021), there is a gap in applying this knowledge to practical farming to mitigate NUE losses (Whetton *et al.*, 2022). Efforts to improve NUE should consider the timing of nitrogen applications and the selection of wheat varieties with higher NUE (Kanampiu *et al.*, 1997; Thomason *et al.*, 2000).

Sustainable Approaches to Nitrogen Management in Wheat Farming:

Sustainable nitrogen management in wheat farming is a critical concern, given the environmental and economic implications of nitrogen use. The literature suggests that conservation agriculture (CA) practices, including minimal soil disturbance, crop residue retention, and crop rotation, can enhance nitrogen use efficiency and reduce environmental impacts (Bhaskar *et al.*, 2021; Shrestha *et al.*, 2020). Additionally, integrated farming systems (IFS) that recycle waste as inputs and precision farming techniques that optimize resource use are also highlighted as effective strategies for sustainable nitrogen management (Kayastha *et al.*, 2024; Sana *et al.*, 2017). Conservation tillage and soil health improvement practices play integral roles in sustainable nitrogen management in wheat farming systems (Six *et al.*, 2004). Interestingly, while conservation agriculture has been shown to reduce ammonia volatilization in wheat (Bhaskar *et al.*, 2021), it is also associated with increased nitrogen-cycling bacterial communities, which can improve soil health and crop productivity (Singh *et al.*, 2021). Furthermore, the integration of eco-friendly agricultural practices, such as biological crop protection and the use of resistant varieties, can contribute to high and sustainable wheat yields, potentially reducing the need for synthetic nitrogen inputs (Rebouh *et al.*, 2023). Sustainable nitrogen management in wheat farming can be achieved through a combination of conservation agriculture, integrated farming systems, and precision farming. These approaches not only improve nitrogen use efficiency but also contribute to the overall sustainability of agricultural systems by enhancing soil health, reducing environmental impacts, and optimizing resource use (Bhaskar *et al.*, 2021; Kayastha *et al.*, 2024; Rebouh *et al.*, 2023; Shrestha *et al.*, 2020; Singh *et al.*, 2021; Sana *et al.*, 2017). Adopting such practices is essential for the transition towards more resource-efficient and environmentally friendly agricultural systems.

Balancing Nitrogen Application to Optimize Yield and Quality:

Balancing nitrogen (N) application is crucial for optimizing both yield and quality in crop production. Studies indicate that while N is essential for plant growth, its over-application can lead to environmental harm and inefficient use, with only about 50% of applied fertilizer being taken up by plants (Bhusal & Thakur, 2022). Conversely, insufficient N can compromise yield and quality, leading to economic losses (Fernandes *et al.*, 2021). Precision management tools such as leaf color charts and sensor-based technologies can assist in predicting crop N needs, thereby enhancing N use efficiency without reducing yield (Bhusal & Thakur, 2022). Long-term

experiments in arid regions have shown that balanced fertilizer treatments, particularly with manure amendments, can stabilize yields and improve N use efficiency (Li *et al.*, 2022). Additionally, optimizing water and N management at the grid scale can contribute to low-carbon agriculture by reducing carbon emissions and improving resource use efficiency (Fan *et al.*, 2022). However, there are contradictions in the optimal N application rates for different outcomes. For instance, a study found that 80 kg N ha⁻¹ maximized yield performance and maintained acceptable N use efficiency, while 160 kg N ha⁻¹ improved grain quality but reduced yield and efficiency (Ierna *et al.*, 2015). Similarly, strategic N management based on plant available water and soil N can enhance yield, grain quality, and profitability, but the optimal rates vary with soil type and environmental conditions (Fabbri *et al.*, 2023). The interaction between tillage and N fertilization methods also influences soil properties and yield, with no-tillage combined with N fertilization showing promising results (Yuan *et al.*, 2022). The synchronization of crop demand with N supply using precision tools is key to minimizing N losses and maximizing use efficiency and productivity (Bhusal & Thakur, 2022). Balanced fertilizer treatments, especially those incorporating organic amendments, are recommended for arid regions to ensure yield stability and soil N retention (Li *et al.*, 2022). Regional water and N management approaches can further support carbon neutrality goals in agriculture (Fan *et al.*, 2022). Ultimately, the choice of N application rate and method must consider the specific crop, soil, and climatic conditions to achieve the best economic and environmental outcomes (Fabbri *et al.*, 2023; Fernandes *et al.*, 2021; Ierna *et al.*, 2015; Yuan *et al.*, 2022). Adopting advanced fertilization methods like surface drip fertilization and optimizing planting density can further enhance yield and resource utilization efficiency (Wu *et al.*, 2024).

Innovative Nitrogen Management Practices for Maximizing Wheat Productivity:

Innovative nitrogen management practices are crucial for maximizing wheat productivity while minimizing environmental impacts. The meta-analysis in Liu *et al.* (2019) suggests that nitrogen input and irrigation significantly increase nitrogen partial factor productivity in winter wheat, with the best results achieved under specific nitrogen and irrigation regimes. Wang *et al.* (2023) supports the notion that nitrogen addition improves wheat yield, grain protein content, and water productivity, with the optimal nitrogen rate being 100–200 kg/ha. Chawla and Balasaheb (2023) emphasizes the importance of integrated irrigation and nitrogen management strategies for

improving wheat crop yields and water use efficiency, highlighting the role of climate, soil, and crop management practices. Zhang *et al.* (2019) presents the CERES-Wheat model as a tool for evaluating management practices, finding that a nitrogen application of 180 kg ha⁻¹ with a specific plant density can optimize yield and nitrogen use under limited irrigation. Li *et al.* (2023) discusses the benefits of integrated rotation-tillage management on wheat productivity and the farmland environment, while Li *et al.* (2022) demonstrates that nitrogen fertilizer precision management can significantly reduce nitrogen input and increase yield. Xin and Tao (2019) offers insights into optimizing Genotype × Environment × Management interactions to enhance productivity and eco-efficiency in the North China Plain, recommending specific nitrogen application rates and irrigation levels. Adak *et al.*, (2023) highlight the potential of exploiting genotype by management interactions to increase wheat yield potential. suggests that no-tillage, crop residue mulch, and appropriate nitrogen and irrigation management can improve yield and water productivity. Lastly, Sarwar *et al.* (2019) indicate that urea management with neem formulations or biofertilizers can enhance nitrogen use efficiency in wheat. The collective information indicates that innovative nitrogen management practices that maximize wheat productivity involve optimizing nitrogen rates, integrating nitrogen with irrigation strategies, considering site-specific factors, and potentially utilizing stabilizing agents like biofertilizers or neem extracts. These practices not only increase yield but also contribute to sustainable agriculture by improving nitrogen use efficiency and reducing environmental risks (Adak *et al.*, 2023; Chawla & Balasaheb, 2023; Li *et al.*, 2022; Li *et al.*, 2023; Liu *et al.*, 2019; Sarwar *et al.*, 2019; Wang *et al.*, 2023; Xin & Tao, 2018; Zhang *et al.*, 2019).

Integrating Technology for Precise Nitrogen Application in Wheat Fields:

Integrating technology for precise nitrogen application in wheat fields is a critical aspect of modern agriculture, aiming to optimize crop yield and minimize environmental impact. Biermacher *et al.* (2006) highlight the economic benefits of sensor-based, site-specific nitrogen application systems over uniform pre-planting applications, demonstrating potential cost savings and yield improvements. Similarly, Vrindts *et al.* (2003) explore precision agriculture methods in grain fields, although the differences in nitrogen doses did not significantly affect yields in the study. Pandey *et al.* (2021) emphasize the role of digital technology in precision agriculture, which

includes variable fertilizer dose application, potentially enhancing the efficiency of nitrogen use in wheat fields. Contradictions arise in the effectiveness of these technologies, as seen in Vrindts *et al.* (2003), where precision agriculture methods did not lead to significantly different yield results. However, the potential for improved nitrogen application efficiency is supported by the findings in Biermacher *et al.* (2006) and the technological advancements discussed in Pandey *et al.* (2021). Additionally, Song *et al.* (2022) suggest that big data analytics and machine learning techniques can further refine precision agriculture practices, potentially improving nitrogen application strategies.

In summary, the integration of technology for precise nitrogen application in wheat fields offers economic and environmental benefits (Biermacher *et al.*, 2006; Pandey *et al.*, 2021), although the effectiveness can vary depending on specific conditions and implementation strategies (Vrindts *et al.*, 2003). The advancement of data analytics and machine learning presents opportunities for further optimization of nitrogen application (Song *et al.*, 2022). Overall, the adoption of these technologies in wheat cultivation is a promising step towards more sustainable and productive agricultural practices.

Future Directions in Nitrogen Management Research for Wheat Production:

Future research in nitrogen management for wheat production should focus on optimizing nitrogen use efficiency (NUE) and recovery efficiency of N (REN) to balance crop productivity with environmental sustainability. Studies have highlighted the potential of integrated nutrient management strategies, including the use of organic matter, biofertilizers, and precision nitrogen application, to improve soil health and crop yields (Panhwar *et al.*, 2018). Additionally, advancements in molecular biology may offer avenues for enhancing NUE through breeding strategies that modulate N-responsive growth-metabolism coordination (Li *et al.*, 2021). Contradictory findings suggest that while some nitrogen management practices have a significant impact on wheat yields and NUE parameters (Santillano-Cázares *et al.*, 2018), others do not show a substantial reduction in N-fertilizer use, although they promote site-specific management (Ji-Ping *et al.*, 2022). Furthermore, the effectiveness of conservation agriculture (CA) in improving soil nitrogen fractions and wheat yields indicates that CA combined with appropriate nitrogen

management can be a viable approach for sustainable wheat production (Thammaiah *et al.*, 2023).

Conclusion:

In conclusion, future research should integrate agronomic practices with technological innovations and molecular breeding to develop sustainable nitrogen management strategies. Emphasis should be placed on practices that enhance NUE and REN without compromising yields, as well as on policies that support the adoption of these practices (Bai *et al.*, 2022; Chawla & Balasaheb, 2023; Grzebisz *et al.*, 2012). Understanding the interplay between genetic factors and nitrogen management will be crucial for achieving sustainable wheat production in the face of global challenges such as climate change and resource scarcity (Gad *et al.*, 2018; Yu *et al.*, 2018).

Overall, a balanced and well-planned nitrogen management approach is crucial for optimizing wheat production, improving grain quality, and ensuring environmental sustainability.

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