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Nitrogen levels in wheat crop production their impact, management, and future perspectives: A review

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Abstract
Nitrogen (N) is one of the most important nutrient components for wheat crop production because it can stimulate very marked growth effects, and increase yield and quality of grains. However, its proper management will be a problem due to the negative impacts that can be given to the environment, such as nitrate leaching and greenhouse gas emission, and because nitrogen fertilizers tend to be a bit more expensive. This paper undertakes a detailed evaluation of the use of nitrogen for wheat production, considering best-management practices focused on environmental sustainability, and it does discuss the impacts of too much nitrogen. Additionally, it discusses advanced technologies intended to enhance nitrogen use efficiency (NUE) toward promoting higher yields without further environmental damage. It discusses sustainable agricultural practice for the future and progresses on the improvement of nitrogen management with a view toward better environmental outcomes.

Keywords: Nitrogen, nutrient use efficiency, nitrate, greenhouse gas

Introduction
Nitrogen (N) is one of the most significant nutrients that control growth vigor and productivity in wheat: it is vital for the key metabolic processes - photosynthesis and protein synthesis - that determine yield and quality in cereal crops. Due to high demand for nitrogen by wheat, appropriate management of this nutrient is very important for successful high production systems and good quality produce. Imbalanced application of nitrogen threatens to generate severe environmental problems such as soil degradation, water pollution, and increases in greenhouse gas emission (Bahmanyar *et al.*2008) [6]. this is a review on the interaction between nitrogen levels and wheat production, focusing on practices in managing nitrogen sustainably.

Wheat has been one of the cereal crops most dependent upon N fertilization to maximize the grain protein content, which is crucial for good baking and processing quality (Barker *et al.*2016) [7]. This review focuses on breeding wheat genotypes that are more yield-stable, produce better grain quality, and have improved NUE, which could reduce some environmental impacts. Of particular interest is the selection of wheat varieties with reduced content of specific storage proteins that contribute relatively little to the desirable processing quality; genome editing may make this feasible (Bender *et al.*1999.) [9] Such breakthroughs and precision nitrogen application approaches may significantly mitigate losses to the environment-especially in wheat as animal feed, where quality requirements are not very strict. While nitrogen fertilizers increase crop yields, it is also an important threat to aquatic ecosystems. (Beri *et al.*1995) [11] Higher levels of nitrogen and phosphorus cause eutrophication, which generates algae blooms, hypoxia, and contaminated groundwater-issues that have public health implications. (Beneduzi *et al.*2012) [10]. Nitrate leached into groundwater or running off into the surface water system can avoid natural buffers, whereas losses into the atmosphere, including ammonia (NH_3), nitrous oxide (N_2O), and nitric oxide (NO), are believed to contribute to acidification, eutrophication, and greenhouse gas emissions (Berry *et al.*2002) [13] Consequently, a further set of BMPs is required to reduce these kinds of losses. Improvement in access to and uptake of nitrogen may be achieved by timing fertilizer application to coincide with crop's demands for nitrogen as well as by

(Boddey *et al*.2003) [15] optimizing application timing in a way that the losses of nitrogen from soil are minimized. Climate change puts pressure on food security as well as crop productivity, and increasing efficiency on arable land by optimizing nitrogen use is one of the pressing answers to the problems. (Chaturvedi *et al*.2006) [17] The aim of more efficient use of agriculture is to increase availability of nutrients, above all in the developing regions, to achieve sustainable agriculture. (Chen *et al*.2006) [18]. It is directed towards improving NUE to provide adequate soil nutrient supplies and fertilizer application practices that respond to crop needs to fulfill the increasing crop demands, ensuring environmental sustainability while being economically viable for the farmer. This will eventually contribute to an improvement in the global resilience of agriculture.

Impact of nitrogen levels on wheat production

Growth characteristics

Soil is the ecological system in which a plant root system interacts with a host of organisms such as insects, earthworms, fungi, and bacteria, which are all important to the health and growth of plants. (Chowdhury *et al*.1978) [20]. A farmer will usually apply chemical fertilizers-for immediate nutrient uptake-and pesticides including herbicides, fungicides, and insecticides for pest and disease control in order to increase crop production (Crook *et al*.1995) [21]. However, overuse of these chemicals has been reported to cause devastating effects on plant development, to alter nutrient uptake, and to pose a risk to human health and ecosystems (Crutzen *et al*.2008) [22]. In such a case, the use of plant growth-promoting bacteria represents an effective ecological approach to the control of pests and improvement in plants (Anjum *et al*. 2008 and Aktar *et al*.2009) [5, 4].

Some important genera of bacteria include Alcaligenes, Arthrobacter, Azospirillum, Azotobacter, Bacillus, Burkholderia, Enterobacter, Klebsiella, Pseudomonas, and Serratia that have been known to promote plant growth. (Dias *et al*.2009) [23]. These microorganisms colonize the rhizosphere. This is the narrow soil region immediately surrounding the roots. Such microorganisms affect plant growth. (Diaz *et al*.2008) [24]. The type of interaction between plants and microbes in the rhizosphere may be symbiotic, nonsymbiotic, which is either beneficial or pathogenic. In this case, microbes release compounds that stimulate the growth of the plant and strengthen its defense mechanisms (Dimkpa *et al*.2009) [25] the rhizosphere is an ideal place for such microbes. The environment is nutrient-rich and stable due to root exudates, less sensitive to fluctuations in temperature, humidity, and light, and so on FAOSTAT. 2014.

Free-living, symbiotic, endophytic bacteria, as well as cyanobacteria (previously known as blue-green algae), may be associated with plants. (Ahemad *et al*.2014) [3]. Probably the most historic and biologically important mutualistic relationship between a plant and a microbe is the symbiosis of Rhizobia with legume roots, which enable atmospheric nitrogen to be fixed. There are five primary genera of Rhizobia: Rhizobium, Sinorhizobium, Bradyrhizobium, Mesorhizobium, and Azorhizobium (Farooq *et al*.2011) [27]. They are all symbiotic inhabitants of nodules on the roots of legumes, where they reduce atmospheric nitrogen to forms that can be used by the plant By (Glick *et al*.2012) [32]

Nitrogen plays a direct role in increasing the performance of plants by providing plants with necessary compounds, regulating growth-promoting hormones, and an activity under anaerobic conditions that favors nutrient uptake due to phosphorus solubilization and siderophore production that chelates iron. (Forster *et al*. 2007 and Francis *et al*. 2007) [28, 29]. Indirectly, it promotes the formation of antagonistic compounds that enhance disease resistance in plants by being protective over the pathogens also (Gill *et al*. 2014) [30]. This multi-functional role of nitrogen underlines the advantages of a biological approach to sustainable agriculture and has healthy soils and productive crops (Gitelson *et al*. 2003) [31].

Grain number, grain filling, and grain quality

Wheat heat and nitrogen stresses are quite complicated, not only in terms of the quantity and grain filling but also from the aspect of grain quality (Goudriaan *et al*.1990) [33]. Excessive application of nitrogen accelerates some processes of growth, thereby reducing grain number and consequently a lower harvest index. (Herridge *et al* 2008) [34] This happens because, with nitrogen-driven growth stimulation, it makes for an imbalance between vegetative and reproductive development efficiency in grain yield production (Hirel *et al*.2006) [35]. Heat stress impacts grain number and size depending on the growth stage at which it occurs; its severity depends upon when the stress happens. (Inman *et al*. 2007 and Ahanger *et al*.2017) [36, 2].

Wheat, at its early growth stages, during spike initiation until anthesis or flowering, is susceptible to heat stress. At this stage, where heat speeds up development time for spikes, less spikelets and grains per spike are obtained. (Ivanova *et al*.2007) [37]. At higher temperatures of 20 °C and above, spiking may occur but will result in lower grain numbers. High temperatures have an inhibitory effect on the development of both pollen and microspores, thus causing male sterility; some wheat varieties cannot form grains when the temperatures are above 30 °C during floret formation. Grain filling, which is the critical period, may also be sensitive to high temperatures (Jabbar *et al*.2009) [39]. Nitrogen and heat have a strong effect on the grain-filling period. While N increases grain filling, it also might shorten the time period for this activity. (Jain *et al*.2024) [24]. Elevated temperatures decrease the time for grain filling; a 5 °C elevation above the optimal of 20 °C reduces the period by as much as 12 d. Night temperatures are highly influential: temperatures in the range of 20 to 23 °C reduce grain filling by 3 to 7 d. **(**Jain *et al*.2024) [40]. Such a large day/night temperature difference of 22 to 32 °C severely reduces the grain-filling rate compared with a cool range of 15 to 25 °C. (Aber *et al*.1998) [1].

Yield loss is as high as 7% for every 1°C increase in temperature from 18 to 21 °C, according to scientists; yield loss is closer to 4%, but temperatures exceed 21 °C, such as in the Great Plains. Ji-(Ping *et al*.2022). Studies conducted in the Great Plains indicated that each 1 °C increase in temperature reduces the reproductive stage by 6% and the grain-filling phase by 5%, which leads to yield and harvest index (HI) reduction. (Kaur *et al*. 2010) [43]. Across nine sites in Europe, it was shown that yield would be lowered by 6% for each 1 °C increase in temperature in spring wheat, and global studies estimated a 5.4% yield loss for each 1 °C rise in temperature. While wheat tolerates some heat, grain-

filling temperatures are sufficiently high to induce some stress (Kobza *et al*.1987) [44].

While there is tolerance to heat, negative effects on grain quality are still present, at least with regard to the accumulation of protein, despite the presence of heat tolerance (Kumar *et al*.2024) [48]. At early grain filling, stress caused by heat can increase protein concentration but decrease key processing qualities like gluten strength. (Ju X-T*et al.* 2009). Such indicators as the retention of lactic acid and peak time in mixogram reflect a lower quality of gluten under heat stress conditions (Kumar *et al*.2023) [47]. Higher protein content under heat stress conditions often coincides with an improved sedimentation index and amino acid levels, but heat periods usually decrease amino acid content, which eventually leads to a low sedimentation index and lower grain quality. On the other hand, nitrogen and heat stresses are central features of wheat development (Kumar *et al*.2024) [48]. Both these stresses interact to ensure grain quantity, size, and quality face certain combined intricate pressures.

The excess nitrogen does indeed affect more than just number of grain, but it might lower harvest index values. Heat stress during critical stages of development can enhance these effects by reducing grain filling as well as quality. (Kundan *et al*.2015) [49]. While high protein content is possible with heat stress at the grain filling stages, such effect is often at the expense of processing quality, which gives an idea of the stress of trying to balance yield and quality as the temperature increases.

Balancing nitrogen application to optimize yield components and quality

Balanced nitrogen application is necessary for optimal yield components and grain quality in wheat, since both depend on N management, growth stages, and environmental factors. The three major factors determining wheat yield are spike density, number of grains per spike, and thousand-grain weight. Nitrogen application at an early stage favors the formation of tillers, which determine the increase in spike density. (Ladha *et al*.2000) [50]. Mid-season sprays, at the time of stem elongation increase the grain number per spike, while late sprays at flag leaf stage improve the TGW thereby supporting grain filling and yield maximization (Lawlor *et al.*2000) [51].

In addition, the amount of applied nitrogen also has a close interaction with grain quality; it influences essential traits such as protein content, gluten strength, and grain hardness. (Leghari *et al*.2016) [52]. In general, late applications of nitrogen in the grain filling stage can increase protein content that enhances baking quality, whereas appropriate levels of nitrogen can improve gluten quality, which is an important trait for baking but excessive application of nitrogen decreases NUE, increases lodging susceptibility, and negatively affects the environment due to increased nitrogen losses. (Lehmann *et al*.2006) [53].

Optimizing N application rates and timing will put farmers in a position to determine good yield-quality balance and ensure environmental sustainability. Precision tools combined with site-specific approaches can be useful for high NUE values, better wheat productivity, and adherence to grain quality standards at the ports of market. (Leigh *et al*.2002) [54].

Nitrogen management in wheat production

Nitrogen Application Rates and Timing

Proper N application rate and timing are fundamentally important in wheat production for the greatest possible yield and grain quality, with optimized NUE (nitrogen use efficiency) and minimized negative environmental impacts (Li *et al.*2021). The average rate of N application for wheat is from 125 to 240 kg/ha, and this rate can vary as adjustments are made for a given soil condition, variety of crop, and desired yield. Site-specific management is allowed through it. It conducts testing and remote sensing in determining the exact nutrient needs by (Lobell *et al*.2007) [56].

Nitrogen application should also be timed. Nitrogen use split during the growth phases will provide the plant with nutrients at the right time to increase both quality and yield (Lucas *et al*.2004) [57]. This would apply in three split strategies; one at either planting/early growth for establishment of good rootings, a second at tillering (Feekes 2-3) to maximize shoot and tiller development, and the third during stem elongation (Feekes 5-6) or flag leaf formation stage. (Yadvinder *et al* 1994) [99]. Early application is increasing the density of spikels, mid-season increases grain number per spike; and its late application fills grains better, thereby increasing thousand-grain weight and also protein contentby (Lukac *et al.*2012) [58].

New precision agriculture tools include crop sensors and variable-rate technology, which further make fine-tuning of nitrogen application possible by varying their rates in relation to real-time crop and soil data. (Ma Jand Li X L *et al.*2007). Such introductions lead to increased NUE, less loss of nitrogen through leaching and volatilization, and reduce the environmental impacts associated with this loss. The yield of wheat is increased when effective rate and timing of nitrogen application are practiced to ensure high yields of better grain quality as well as reduced environmental impact (McCauley *et al.*2009) [60].

Integrated nutrient management (INM)

INM combines organic, inorganic, and biological sources that would maximize nutrient availability while improving the fertility status of the soil and reducing adverse environmental impacts. The goal is to maintain or increase crop yields by matching better crop requirements with inputs by respecting soil health and sustainable use of resources (Moges *et al*.2005) [61].

The balanced use of chemical fertilizers, organic materials such as compost, farmyard manure and crop residues, and biofertilizers like nitrogen-fixing and phosphorus-solubilizing microbes are at the heart of INM. (Ortíz-Castro *et al*.2009). Fertilizers provide an immediate supply of nutrients absorbed by crops, whereas nutrient supplies are released progressively by organic inputs, thus improving soil structure, microbial diversity, and water retention. Biofertilizers improve the availability of both nitrogen and phosphorus and generally promote health in the soil (Oteino *et al*.2015) [63].

For instance, in legumes it is the nitrogen-fixing bacteria like Rhizobium whereas in cereals it is nitrogen-fixing bacteria like Azotobacter. Both these types of bacteria naturally enrich the soil with nitrogen instead of synthetic N-fertilizers. Similarly, phosphorus-solubilising microbes help convert phosphorus of the soil in to its more accessible

forms thereby increasing the efficiency of phosphorus for plants (Panhwar *et al.*2019) [64].

The use of INM also incorporates the timing and methods of nutrient application. Coordinated with crop growth stages and split applications, techniques such as deep placement or fertigation are employed, which improve the use efficiency of nutrients applied while losses via leaching or volatilization are minimized (Paulsen *et al.*1994) [67]. So, based on information from soil testing and other precision agriculture tools, SSNM will guide each particular field on how to manage it to avoid overuse and underuse by (Patel *et al.*2023) [66].

Role of potassium in nitrogen use efficiency

Potassium (K) is essential to increase NUE in crops, especially in the intensive application of nitrogen to such crops as wheat. NUE refers to the ability of a crop plant to absorb N and assimilate it into growth and yield components-productivity and environmental sustainability. (Welche *et al.*1999) [96]. Potassium has been often called the "quality element" because it plays an essential role in nitrogen uptake, assimilation, and crop health overall by (Patel *et al.*2023) [66].

The most important function of potassium is the activation of enzymes, which plays a crucial role in protein synthesis. Since nitrogen is an element of amino acids and proteins, potassium-driven enzyme activity facilitates the conversion of absorbed nitrogen into amino acids, hence helping in the production of proteins. (Pettigrew *et al.*2008).Potassium at optimum levels increases the conversion of absorbed nitrogen into biomass whereby the yields are increased and the crop quality improved by (Welch *et al.*2013) [97].

Potassium also affects the movement of water and nutrients within plant tissues; therefore, it promotes photosynthesis and nutrient transfer by (Prather *et al.* 2001). During nitrogen assimilation, potassium facilitates the translocation of nitrogen from the roots to the shoots where it is needed for growth in the formation of chlorophyll and other compounds of growth. This efficient movement ensures optimal use of nitrogen in the whole plant with reduced possible losses such as leaching and volatilizationby (Pushpalatha *et al.*2008) [70].

Potassium also makes the plants resistant to environmental stresses, such as drought and disease whose impact can result in low efficiency of uptake and utilization of nitrogen. (Raun *et al.*2001) [71]. Under stress, imbalances of nutrients also impair nitrogen metabolism; however, potassium ensures that, under stress, plants retain water, and the effects of pests and diseases are kept at bay hence ensuring constant nitrogen uptake and utilization. (Robertson *et al.*2000) [72].

Thus, potassium is the key ion for the maximum utilization of NUE through increased assimilation of nitrogen, proteins, and enhancement of stress tolerance. (Robertson *et al.*2004) [73]. Balanced applications of potassium and nitrogen include the integrated nutrient management approach that supports higher crop yields, efficient nitrogen utilization, and sustainable agriculture, with minimum waste of nutrients as well as less adverse impact on the environment (Saharan *et al.*2011) [74].

Loss of nitrogen use efficiency in wheat

In wheat, the nitrogen use efficiency is influenced by several pathways in the loss of nitrogen such as volatilization, leaching, denitrification, and surface runoff. (Saifullah *et al.*2002) [75]. Nitrogen loss in gaseous form has been observed to be appreciable between anthesis and post-anthesis with notable amounts during this period. (Santillano-Cázares 2018) [76]. In the case of winter wheat systems, several studies have been conducted to determine the NUE, which has been found to be higher as the wheat is harvested before anthesis as forage rather than as grain since this does not allow significant nitrogen loss that often takes place after flowering (Sharma *et al.*2008) [77].

It is possible to specify at least some of the physiological and molecular factors controlling NUE like DEGs related with carbon and nitrogen metabolism in wheat genotypes with differing NUE values, but practical applications for farming are still not well in hand. Spatial and temporal heterogeneity of NUE also exists; for instance, state-level NUE for winter wheat is positively trended in the last few decades that may partly facilitate reducing agricultural nitrogen losses (Shewry *et al.*2009 and Welch *et al.*1999) [78, 96].

In general, the losses of nitrogen in wheat are mainly through volatilization, leaching, and denitrification but major losses occur post-anthesis. (Sidhu *et al.*2005) [79]. Although information regarding NUE from research at the molecular level is available, there is a need to close this knowledge gap that exists between these aspects of research and the on-farm practices with an aim to check the losses in NUE. (Singh *et al.*2024). NUE enhancement relies essentially on strategically timed application of nitrogen combined with selection of wheat varieties that have an intrinsically higher NUE.

Integrating technology for precise nitrogen application in wheat fields

Use technology for accurate nitrogen application in wheat. Improving yield and reducing environmental impact should be the focus while adopting increased sustainable output. Nitrogen is an essential nutrient needed by wheat during its growth, but if used excessively, soil and water pollution will result from it; on the other hand, incomplete application may hinder crop productivity (Sofi eld *et al.*1974) [81].

Advanced equipment, such as remote sensing, drones, and satellite imagery, enables farmers to monitor changes in the amount of nitrogen over extensive agricultural areas in real time. (Sofi eld *et al.*1977) [82]. This equipment assists them to identify and maintain sections of the field that may have either less or more amounts of this nutrient. This variable rate approach, therefore ensures that all fields receive only the amount of nitrogen each section requires. (Souza *et al.*2015) [83].

These systems utilize high-tech farming precision technologies; for instance, GPS-guided tractors and sprayers for fertilizers' application. (Srinivasarao *et al.*2013) [84]. These systems take data feed from sensors meant to monitor the soil's nitrogen levels, crop health, and weather conditions to adjust the application rate of nitrogen. Soil health sensors also provide knowledge regarding the availability of nutrients in the soil to the farmer in real-time; the information is helpful in making correct decisions as regards when and how much to apply nitrogen. (Tabatabaei *et al.*2016 and Wang *et al.* 2016) [85, 94].

Other significant involvements are by machine learning algorithms and artificial intelligence in nitrogen management refinements. (Tashiro *et al.*1990) [86]. AI gives predictions about the nitrogen requirements for wheat

varieties of different types, soil types, and weather patterns using a large amount of data. In addition to the ever-increasing crop yields and saving costs incurred due to fertilizers, this convergent approach minimizes the environmental toll of nitrogen, thus leading to sustainable farming practices.by (Thammaiah *et al*. 2023) [87].

Future directions in nitrogen management research for wheat production

Future research on nitrogen management for wheat should concentrate on optimizing both NUE and nitrogen recovery efficiency: the pursuit of a balance that allows crop productivity without compromising environmental sustainability. (Uraguchi *et al*.2012) [88]. An outstanding component of INM is improved nitrogen management by an integration of organic matter and biofertilizers with precision nitrogen application techniques; such methods are in development for soil fertility improvement and increased wheat yield (Vijayalakshmi *et al*.2010) [89].

There is also scope to include advanced molecular biology techniques to enhance NUE. Breeding for nitrogen responsiveness can be used to make genetic improvements more in line with changes that occurred in the plant's growth and metabolism as the crop was developed, especially in wheat. Walker *et al.*2003) [90]. This has proved to be a mixed bag. While some of the nitrogen management options have drastic effects on wheat yield and NUE, others do not necessarily reduce the amount of nitrogen fertilizer needed but promote site-specific management. Therefore, this implies that the effectiveness of the practices may be contingent upon local conditions or environmental factors (Walsh *et al*.2013) [91].

The effects of Conservation Agriculture (CA) on soil nitrogen fractions and wheat grain yields offer a very good opportunity to combine CA with proper N management strategies. (Wang *et al*.2003) [92]. This integrated approach may well add up to a more sustainable wheat production system capable of delivering high yields while minimizing the negative impacts on the environment. Continued refinement of nitrogen management practices, together with introduction of new technologies such as molecular breeding, would indeed hold sound potential for further improvement of nitrogen efficiency and ensure sustainability of wheat production systems in the future. (Wang *et al*.2015 and Waters *et al*.2009) [93, 95].

Conclusions

This review concludes no single method will be sufficient to boost nitrogen levels in isolation but a combination approach will be more effective. Ultimately, optical sensors may prove to be beneficial in increasing the level of nitrogen and farmer profit with time, but only if data from multiple sites is accurately acquired and interpreted with variability in soil, climate, and cultural practice in mind, followed by development of a resilient yield-predicting model. Possible key factors may include sensor-based in-season nutrient management integrated with soil testing at the commencement of planting, and split application of N. Furthermore, extending sensor technology and developing algorithms might fulfill the need for upscaling models that are more stable and reliable. Precipitation data, although collected in a manner more feasible than retrieving soil moisture data, may also be helpful in fine-tuning sensor models.

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