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The Impact of Nitrogen Fertilization on Yield and Quality of Different Wheat Varieties

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Abstract Nitrogen fertilizer application plays a crucial role in optimizing wheat production, affecting both yield formation and grain quality. However, balancing these two goals remains challenging due to differences in the response of different varieties to nitrogen fertilizer and the physiological trade-offs between yield and quality traits. This study systematically summarizes the current research on the effects of nitrogen fertilizer application on different wheat varieties, focusing on growth stage regulation, root development, nutrient absorption, protein accumulation, starch synthesis and overall grain quality. It explores the genetic basis of nitrogen use efficiency (NUE) and identifies key traits and quantitative trait loci (QTL) that control nitrogen uptake, utilization and response in high-gluten, medium-gluten and low-gluten wheat. Through case studies of some wheat genotypes, it illustrates how the adaptability of varieties to nitrogen input affects yield and processing quality under different cultivation systems. This study hopes to combine genomic tools with precision fertilization practices to provide a sustainable way to achieve high yield, high quality and reduced nitrogen input in wheat production systems.

Keywords Nitrogen fertilization; Wheat varieties; Grain quality; Nitrogen use efficiency; Yield performance

1 Introduction

Wheat is an important food crop in the world. Today's agriculture requires not only high yields but also good quality to meet the dual needs of eating and processing (Zörb et al., 2018; Martre et al., 2024). These two goals are often linked, but sometimes they conflict with each other. For example, if the yield is high, the protein content may be low, affecting the quality and nutrition of the flour. Farmers and breeders hope to grow more and better wheat. High production capacity ensures food supply and can also make planting more profitable; and the quality of wheat, such as protein content, gluten strength, and mineral absorption, determines what kind of food it is suitable for, and is also related to its nutritional value (Gaile et al., 2018). However, it is not easy to achieve these two goals at the same time, because sometimes improving one will affect the other. For example, applying more fertilizer for high yield may dilute the protein content.

Nitrogen (N) is one of the most important and most easily deficient nutrients in wheat growth. It has a great impact on yield and grain quality (Wang et al., 2023; Yokamo et al., 2023; Martre et al., 2024). If nitrogen is applied properly, it can increase protein content, improve dough quality, and increase yield. However, if too much or too little is applied, the nitrogen fertilizer will not be worthwhile, not only affecting wheat growth, but also polluting the environment (Walsh et al., 2022; Xu et al., 2024). In addition, different wheat varieties respond differently to nitrogen fertilizers. Some varieties have strong nitrogen absorption capacity, while others are not so good. Therefore, if you want to ensure both yield and quality, you must understand the performance of each variety on nitrogen fertilizers in order to scientifically formulate a fertilization plan.

This study reviews the latest research progress on how nitrogen fertilizer affects the yield and quality of different wheat varieties, and explores the physiological mechanisms, variety differences and agronomic measures that mediate these effects in order to optimize nitrogen fertilizer management strategies to achieve the dual goals of high yield and high quality, while emphasizing the importance of variety selection and practices tailored to local conditions.

2 Effects of Nitrogen on Wheat Yield Formation

2.1 Regulation of growth stages and leaf area index by nitrogen

Nitrogen fertilizer directly affects how wheat grows. After applying nitrogen fertilizer, the leaves are greener, photosynthesis is stronger, the leaves age slower, and the leaves grow larger, so that the leaf area index (LAI) will also increase, which will eventually help to increase dry matter mass and yield (Figure 1) (Hong et al., 2021; Noor et al., 2023). During the wheat booting or flowering period, if the amount of nitrogen fertilizer is appropriate, the photosynthetic efficiency of the leaves will increase, which can increase biomass and increase grain yield (Luo et al., 2021). In addition, nitrogen fertilizer can make the plants taller, the leaves are more and larger, and it is easier to absorb sunlight, which is very helpful to increase yield.

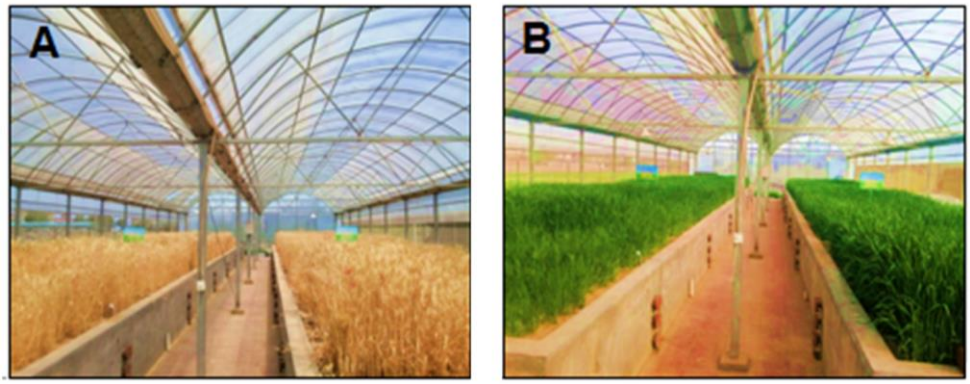

Figure 1 (A) Maturity stage of greenhouse winter wheat. (B) Jointing stage of greenhouse winter wheat (Adopted from Noor et al., 2023)

2.2 Role of nitrogen in root development and nutrient uptake

Nitrogen fertilizer also has an effect on the root system. Only when the roots grow well can they absorb more water and nutrients, which is very critical to increasing yield (Li et al., 2024). If fertilization is done properly, the aboveground part of the plant can grow faster and the nitrogen content in the grain will increase. However, if too much nitrogen is used, the dry matter and nitrogen may not be transported from flowering to maturity, and the yield will decrease instead of increase, and the fertilizer will be wasted. In addition, nitrogen fertilizer can also allow wheat to better utilize the nitrogen originally remaining in the soil, which can not only increase yield but also not cause too many environmental problems (Xu et al., 2020).

2.3 Varietal differences in yield responses to nitrogen

Different wheat varieties also perform differently after using nitrogen fertilizer, which is related to their genetic characteristics and ability to absorb and utilize nitrogen (Walsh et al., 2022). Some varieties respond particularly well to a certain nitrogen fertilizer, such as urea and nitrate nitrogen mixed application. This combination is very effective in improving yield and nitrogen use efficiency (Cui et al., 2023). Moreover, different environments, soils and management methods will also affect the effect of nitrogen application. Therefore, the specific fertilization should be determined according to local conditions and the varieties used, which will make it easier to increase the yield (Wang et al., 2023; Yokamo et al., 2023; Feyisa et al., 2024).

3 Influence of Nitrogen on Wheat Quality Traits

3.1 Protein accumulation and gluten strength

Nitrogen fertilizer is important for increasing protein in wheat grains. It can increase the total protein in the grains and increase the content of some major proteins, such as alcohol-soluble proteins and gluten. These proteins affect gluten strength and also affect baking performance (Zörb et al., 2018). Generally speaking, if nitrogen fertilizer is used appropriately, such as foliar spraying during flowering, the protein and gluten content can be increased. Moreover, varieties with low protein content are more sensitive to changes in nitrogen fertilizer (Iannucci et al., 2018; Gu et al., 2023). But this is not the case. Sometimes too much nitrogen absorption will reduce the gluten index, indicating that there may be a conflict between protein content and actual gluten quality (Chen et al., 2022).

3.2 Nitrogen effects on starch synthesis and kernel weight

Nitrogen fertilizer also affects starch synthesis in wheat, which in turn affects grain weight. Starch is an important part of flour processing, and large grain weight can also affect total yield. If more nitrogen is applied, the amount of amylose in the grain may decrease, which will change the properties of the dough (Gu et al., 2023). In addition, grain size and weight are also related to nitrogen levels. Some QTLs that control these traits have been found, which are also related to resistance to nitrogen stress (Cui et al., 2015). However, it should be noted that protein content and thousand-grain weight are often negatively correlated, that is, more protein may reduce grain weight (Fan et al., 2020).

3.3 Combined effects on processing and nutritional quality

The amount of nitrogen fertilizer will affect both the processing quality and nutritional value of wheat. For example, an appropriate amount of nitrogen fertilizer can make the dough form better and more stable, which is very important for making bread or noodles (Gu et al., 2023). Nitrogen fertilizer can also reduce phytic acid, so that trace elements such as iron and zinc are more easily absorbed by the human body. For colored wheat, applying less nitrogen may make anthocyanins more, which is good for health. However, if anthocyanins are increased, processing traits may be worse (Yan et al., 2024). All these indicate that different varieties, fertilizer amounts and growth environments must be well matched to take into account both processing quality and nutritional value (Iannucci et al., 2018; Fan et al., 2020).

4 Varietal Differences in Nitrogen Use Efficiency

4.1 Nitrogen absorption and utilization efficiency

Different wheat varieties perform differently in terms of nitrogen absorption and utilization. Nitrogen absorption efficiency refers to the ability of plants to absorb nitrogen from the soil. Nitrogen use efficiency refers to the ability of plants to convert absorbed nitrogen into food. The combination of these two abilities determines the overall nitrogen use efficiency (NUE) of a variety. Some varieties absorb more nitrogen but convert less nitrogen, while others are good at both. For example, in soft red winter wheat, nitrogen use efficiency can contribute more than 50% to yield increases (Barraclough et al., 2010). Some of these differences come from genes, and some are also related to the environment such as climate and soil. But in general, the genetic characteristics of the variety play a key role (Ivić et al., 2021).

4.2 Genetic basis of nitrogen responsiveness

Different wheat varieties also have great differences in their responses to nitrogen fertilizers. Some varieties grow faster and have higher yields when more fertilizer is applied; some varieties perform well even if less nitrogen fertilizer is applied. This response to nitrogen is related to the genetic genes of the variety itself. With the development of breeding technology, many new varieties have performed better and better in nitrogen utilization, especially in high yield (Ivić et al., 2021). The key factors that determine these abilities include the number of grains per ear, the nitrogen harvest index (that is, how much nitrogen is absorbed and converted into grain), and whether stable output can be achieved under different nitrogen fertilizer levels (Barraclough et al., 2010). These research results show that it is possible to adapt to different agricultural models, such as intensive planting or low-input farming, by breeding varieties specifically suitable for efficient nitrogen use.

4.3 Agronomic traits of efficient nitrogen-use genotypes

Varieties with high nitrogen utilization rates generally have several characteristics: high yield, fast nitrogen absorption, and good adaptability. Regardless of whether more or less nitrogen fertilizer is used, these varieties tend to maintain stable performance. This also shows that when breeding new varieties, whether the target is high-fertilizer land or low-fertilizer land, improving nitrogen utilization efficiency is a worthwhile direction (Büchi et al., 2016; Ivić et al., 2021). In addition to efficient nitrogen uptake and use, these varieties often have other advantages, such as disease resistance, drought tolerance, and low weed pressure, which are conducive to use in organic farming or low-input systems. By combining these traits with nitrogen use efficiency in breeding, it is possible to breed wheat varieties that are both high-yielding and environmentally friendly.

5 Timing and Method of Nitrogen Application

5.1 Effect of split application and topdressing

During the growth of wheat, applying nitrogen several times is more effective than applying it all at once, especially after the booting stage, which is very helpful for yield and quality. Global studies have found that this practice can increase the protein, wet gluten and dough stability in the grain, and cause less yield loss than a single fertilization (Wu et al., 2022). For example, some studies suggest applying half of the fertilizer at the time of emergence and half at the tillering stage; some choose to apply fertilizer twice at the tillering stage and the booting stage, which can increase both yield and protein content. Which one is better depends on the local climate and soil conditions (Derebe et al., 2022). Topdressing before spikelet differentiation can also improve the development ability of the spike, thereby increasing yield (Aryan et al., 2024). In addition, split fertilization can also reduce the loss of nitrogen fertilizer, especially when using water-saving irrigation, this method can improve the utilization efficiency of nitrogen fertilizer (Zhang et al., 2022).

5.2 Comparison between deep placement and surface application

The method of fertilization can also affect wheat growth and the amount of weeds. Compared with spreading fertilizer on the surface, applying nitrogen fertilizer 10 cm deep between crop rows, such as strip fertilization or spot fertilization, can make wheat grow better and reduce weeds. Deep nitrogen fertilizer allows wheat to absorb more nitrogen, while weeds grow less and are less likely to spread seeds, which is more conducive to establishing an efficient and sustainable production system.

5.3 Impact of controlled-release vs. conventional urea

Controlled-release nitrogen fertilizers, such as coated urea, have many advantages over ordinary urea. They can release nitrogen slowly, which is more in line with the absorption rhythm of wheat and is not easy to cause waste (Wang et al., 2023). Studies have found that if controlled-release fertilizers are used, the amount of fertilizer applied is increased, or a second topdressing is chosen after heading, both yield and quality are usually better, especially in medium-textured soils and relatively moist environments.

6 Case Studies: Nitrogen Response in Selected Wheat Varieties

6.1 Nitrogen fertilizer regulation experiment of high-yield strong-gluten varieties

Some high-yield strong-gluten wheat varieties respond significantly to nitrogen fertilizer. There are obvious differences in the ability of these varieties to absorb and use nitrogen, which is mainly determined by genetics (Mahjourimajd et al., 2016; Ivić et al., 2021). For example, some varieties can use nitrogen better under appropriate fertilization conditions, and both yield and quality are improved, which means that their "Nitrogen Efficiency Comprehensive Score (NECS)" is relatively high (Ding et al., 2023). This variety has the most obvious yield increase effect under high nitrogen application rates, and their genetic background supports faster nitrogen absorption and protein accumulation. For farmland that pursues high yield and high-quality strong gluten, this variety is very suitable for intensive management.

6.2 Quality performance of medium-gluten varieties under different nitrogen concentrations

The yield and quality of medium-gluten wheat are greatly affected by nitrogen fertilizer, and different varieties respond differently (Ivić et al., 2021). Through field trials in different seasons, it was found that these varieties can be divided into several groups. Some varieties have stable yields within a certain range of nitrogen application, while others are very sensitive to changes in fertilizer application. The researchers also found gene loci related to nitrogen response in these varieties, which can be used to guide breeding. By selecting these genes, nitrogen utilization efficiency can be improved and the varieties can be more adaptable to different fertilization schemes (Ding et al., 2023).

6.3 Low-nitrogen environmental adaptability and nitrogen-saving potential of weak-gluten varieties

Weak-gluten wheat generally does not pursue high yield or high protein, but pays more attention to nitrogen utilization efficiency and stress resistance (Figure 2) (Büchi et al., 2016; Yan et al., 2021). Some varieties can still produce stable output with little nitrogen fertilizer, showing good low-nitrogen adaptability. For example,

measured by "yield stability index (YSI)" and "geometric mean yield (GMP)", these varieties still perform well in nitrogen-deficient environments (Tyagi et al., 2020). They have some special mechanisms in their bodies, such as certain genes that are activated under low nitrogen, which helps them grow better. Such varieties are suitable for breeding projects in low-input, sustainable agricultural systems.

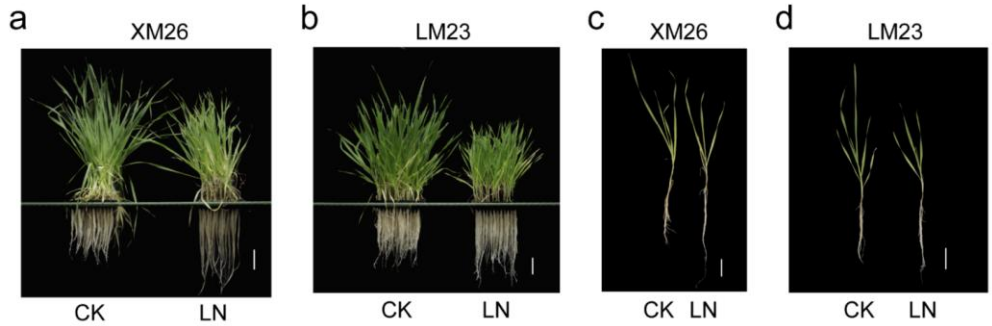

Figure 2 Growth phenotypes of XM26 and LM23 under normal (CK) and low-nitrogen (LN) conditions. (a,c) The phenotype of XM26 after CK and LN treatments for 23 d. Bar = 5 cm. (b,d) Phenotype of LM23 following CK and LN treatments for 23 d. Bar=5 cm (Adopted from Yan et al., 2021)

7 Concluding Remarks

Wheat yield and quality are closely related to nitrogen fertilizer application and variety characteristics. Different wheat varieties have different nitrogen absorption and utilization efficiencies. Some varieties respond quickly to nitrogen and grow well, while others do not. This difference is determined by genes on the one hand and by the environment on the other. However, varieties that perform well under high nitrogen conditions usually perform well under low nitrogen conditions, which means that they are relatively stable under different fertilization environments. With the development of breeding technology, nitrogen use efficiency (NUE) is also gradually improving. The main reason is that higher-yielding varieties are selected during the breeding process.

Now we can find out which gene regions (QTLs) and genetic markers are related to nitrogen response and NUE through phenotyping, genetic mapping and whole-genome association studies. These tools can help breeders more accurately and select varieties suitable for different fertilization conditions, especially those suitable for low-input, sustainable cropping systems. In addition, proper management of nitrogen fertilizers, such as controlling the time, amount and method of fertilization, can also improve nitrogen use efficiency and reduce environmental impact. Especially when these practices are combined with wheat varieties that use nitrogen efficiently, the effect will be more obvious.

To achieve high yield, good quality and less fertilizer, we need to choose wheat varieties that are stable under different fertilization methods and have high nitrogen utilization efficiency. When breeding, we can also consider adding traits such as disease resistance, drought resistance and weed resistance. Such varieties are more suitable for low-input or even organic farming methods. We can use new technologies, such as advanced phenotyping platforms and genetic analysis tools, to find important QTLs related to nitrogen response, and then use these traits in breeding. At the same time, we should promote precision fertilization techniques, such as split fertilization and fixed-point fertilization, so that the supply of nitrogen fertilizer is more in line with the needs of crops and the weather conditions at the time. Combining organic and mineral fertilizers for soil management helps to protect soil health and lay the foundation for long-term and stable wheat production. These practices used together can help us achieve the goals of high, stable, high-quality and low-pollution wheat, and promote the development of the entire wheat production in a sustainable direction.

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Conflict of Interest Disclosure

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

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