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Cultivating High-Quality Wheat Varieties with High Nutritional Value

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Abstract Wheat, as one of the most widely cultivated and consumed staple crops worldwide, plays a critical role in global food security and human nutrition. In this study, we explored comprehensive strategies for cultivating high-quality wheat varieties enriched with nutritional value, addressing the growing demand for healthier dietary options. Our approach integrates advances in genetic research-including gene mapping, transcriptomic profiling, and gene editing-with biofortification breeding methods and improved agronomic practices. We investigated genetic determinants for key traits such as protein, zinc, and iron content, and examined the application of GWAS and CRISPR technologies to enhance nutritional traits. Additionally, we assessed the impact of soil management, irrigation, and post-harvest practices on wheat quality. Case studies from India, Ethiopia, and China illustrate successful deployment of nutrient-rich wheat varieties and their implications for public health and food systems. Despite challenges such as yield-quality trade-offs and market constraints, the integration of multi-omics tools, precision agriculture, and global collaboration holds promise for future innovations. This study highlights the need for interdisciplinary efforts and policy support to ensure sustainable development of nutritionally superior wheat cultivars.

Keywords Wheat biofortification; Nutritional quality; Genetic improvement; Agronomic practices; Precision agriculture

1 Introduction

Wheat (*Triticum* spp.) is a very important food crop in the world. The staple food that many people eat every day, such as steamed bread and bread, is made of wheat. It can adapt to various climates and can be grown in many places, so the planting area is very large. According to research, wheat provides about half of the world's food calories (Khalid et al., 2023). Because wheat has high yield and strong adaptability, it is particularly important in some resource-poor areas (Hao et al., 2024). Wheat can be used to make a lot of things. Not only bread, but also noodles, pasta and other foods. So it accounts for a large part of the world's diet (Graziano et al., 2019).

In addition to providing energy, wheat also contains a lot of nutrients. For example, protein, dietary fiber, and some important minerals such as iron, zinc and magnesium (Shamanin et al., 2024). However, the nutritional content of different types of wheat is not the same. Some old varieties, such as einkorn and emmer, contain more antioxidants and plant compounds than today's ordinary wheat, which may be more beneficial to the body (Mougiou et al., 2023). Wheat also contains gluten, which is critical to the quality of bread. But for some people, this ingredient can cause discomfort, such as celiac disease. So when breeding, in addition to considering yield and processing performance, we must also pay attention to its impact on health.

The goal of this study is to find out how to breed more nutritious wheat varieties. We will study the genetic and environmental factors that affect wheat nutrition, and we will also see if traditional varieties and local varieties can help modern wheat improve nutrition. At the same time, we will analyze the biochemical composition and agronomic characteristics of wheat, hoping to find good genetic resources and breeding techniques to help breed nutritious and high-quality wheat varieties. Ultimately, these studies can provide references for future breeding work, allowing people to eat healthier and help improve food security.

2 Genetic Basis of Wheat Nutritional Quality

2.1 Genetic determinants of protein and micronutrient content

The nutritional composition of wheat is determined by many genes. These genes affect the protein and various trace elements in the grain, such as iron, zinc and magnesium. The protein content (GPC) in wheat is one of the important indicators for judging whether it is nutritious. Studies have found that some gene loci (called SNPs) are distributed on chromosomes 1D, 3A, 3B, 3D, 4B and 5A, which are related to protein synthesis and nutrient transport processes (Kartseva et al., 2023). In addition, genes are also involved in wheat's absorption of macronutrients such as nitrogen, phosphorus and potassium. For example, SNPs related to these nutrients have also been found on chromosomes 1A, 1B, 1D and A3 (Aljabri and El-Soda, 2024). This information is very helpful for breeding, especially when you want to improve wheat nutrition.

2.2 Biofortification methods in wheat breeding

Nowadays, biofortification is a widely used breeding method. Its goal is to select wheat varieties that contain more iron, zinc, and magnesium. Through these varieties, we can cultivate wheat with higher nutrition (Rabieyan et al., 2023; Petrović et al., 2024). Different varieties of wheat vary greatly in nutrient content. These differences can be used for selection during breeding. Not only common wheat varieties, but also some wild wheat and local old varieties are nutritious, and their genetic resources are very valuable. Introducing these excellent genes into modern varieties can improve the overall nutritional level of wheat (Zeibig et al., 2024). This method is particularly useful in some developing countries because many people rely on wheat as their staple food, but their nutritional intake is insufficient.

2.3 Genomics and transcriptomics tools for quality improvement

Now that technology is becoming more and more advanced, there are more tools for improving wheat. Technologies such as "Genome-wide Association Study" (GWAS) and "Quantitative Trait Loci Location" (QTL) can help us find genes related to protein content and mineral accumulation (Figure 1) (Lou et al., 2020; Fradgley et al., 2022). With this data, breeders can more accurately select the desired varieties. Tools such as SNP chips and transcriptome analysis can also tell us which genes play a role in the synthesis and transport of nutrients (Khalid et al., 2023). These technologies can make breeding work more targeted and efficient, and help to improve the nutritional quality of wheat to a new level.

3 Agronomic Measures to Improve Wheat Quality

3.1 The role of soil and fertilization in nutrient absorption

For wheat to absorb more nutrients, the soil must be good and the fertilization must be reasonable. Especially nitrogen fertilizer, it has a great impact on the protein in the grain and the overall quality. If the amount of nitrogen fertilizer and the time of fertilization can be arranged well, it will not only make the wheat grow better, but also reduce pollution (Liu et al., 2018; Melash and Ábrahám, 2022). In addition to chemical fertilizers, organic fertilizers and crop rotation are also useful. Using organic fertilizers can improve soil structure, make the soil healthier, and nutrients are more easily absorbed. Crop rotation can also help restore soil nutrients, thereby improving wheat yield and nutritional quality (Li et al., 2023).

3.2 Impact of irrigation and crop management

Water is important for wheat, and planting methods can also affect its yield and quality. In arid areas, if water can be applied once and for all at the right time, coupled with deep loosening of the soil and proper use of fertilizers, wheat leaves will be healthier and photosynthesis will be stronger, so that the yield will naturally increase (Huang et al., 2024). In addition, the planting method can also be adjusted, such as appropriately changing the density of sowing. This can help wheat make better use of rainwater, especially in places where rainfall is irregular. This practice allows wheat to use water when it needs it, is less susceptible to drought, grows stronger, and has a more stable yield (Yang et al., 2021). In the final analysis, these methods are all about making water and fertilizer use more accurately and truly use them when and where wheat needs them most.

3.3 Impact of post-harvest handling and storage

After wheat is harvested, how it is handled will also affect its quality. If the temperature and humidity can be controlled well, the wheat will not spoil easily and the nutrients can be preserved. However, if it is not handled properly, such as when the soil is compacted too tightly during harvesting, or the ground is too lumpy, it will not only affect the quality of the wheat, but may also make the soil hard, affecting the next season's planting (Al-Shammary et al., 2023). Therefore, after harvesting wheat, it is best to adopt some methods to protect the soil. For example, light tillage, try not to disturb the soil structure, and add scientific storage methods, which can help the wheat retain nutrients and make the quality more stable.

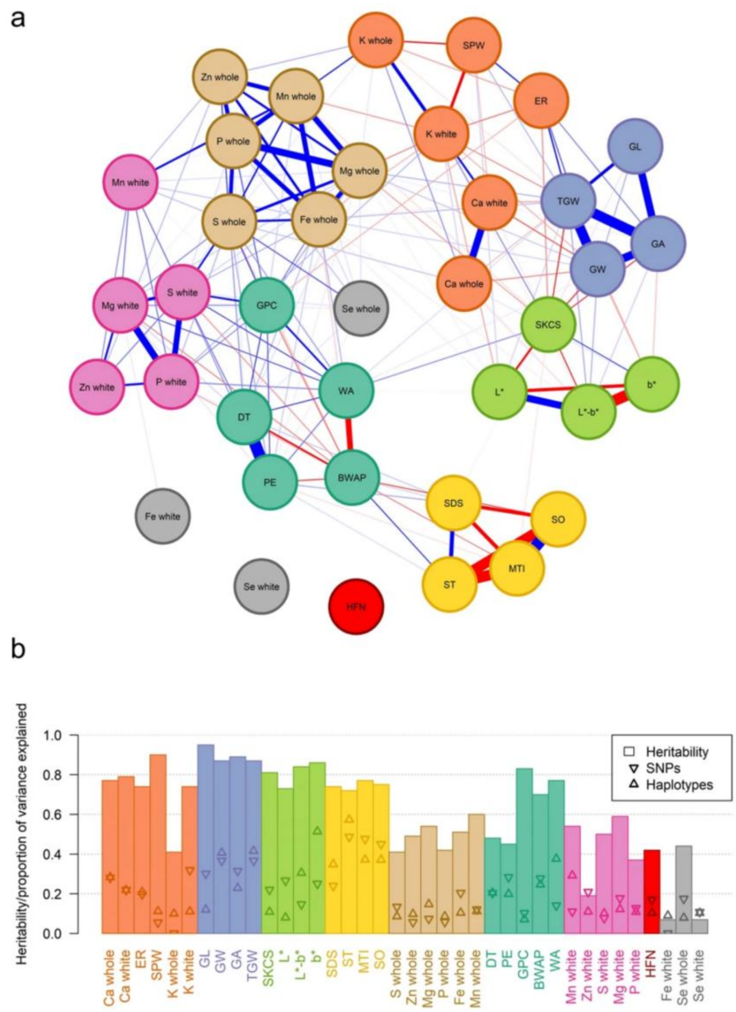

Figure 1 Relationships among traits and the proportion of the trait heritability explained by QTL (Adopted from Fradgley et al., 2022)

Image caption: a: Network analysis of all analysed milling, baking and micronutrients traits across two trial years identify eight distinct groups. Blue and red connecting lines indicate positive and negative correlations, respectively and line width is proportional to correlation strength. Only correlations with $p < 0.001$ are shown. b: Proportion of phenotypic variation explained by the broad sense heritability as well as all QTL included in a full model for SNP and haplotype-based analysis for meta-analysis across two trial years for all traits. GPC=Grain protein content (%); SPW specific weight (kg hl-1), SKCS single kernel characterisation system hardness, ER extraction rate (%); L*=Flour whiteness (Tristimulus L*); b*=Flour yellowness (Tristimulus b*); L*-b*=overall flour colour (Tristimulus L*-b*); HFN=Hagberg Falling Number (s); GA=MARVIN grain area (mm^{-1}); GL=MARVIN grain length (mm); GW=MARVIN grain width (mm); TGW=MARVIN thousand grain weight (g); BWAP=DoughLab Bandwidth at Peak; DT=DoughLab Development time (s); MTI=DoughLab mixing tolerance index; PE=DoughLab Peak Energy; SO DoughLab Softening; ST=DoughLab Stability; WA=DoughLab Water absorption (%); SDS=SDS Sedimentation (ml); whole=mineral concentration in whole meal flour (mg/kg); white=mineral concentration in refined white flour (mg/kg) (Adopted from Fradgley et al., 2022)

4 Cultivate High-Quality and High-Nutrition Wheat Varieties

4.1 Integration of quality and yield traits

When breeding, we should not only look at how much grain wheat can produce, but also whether it is nutritious. In the past, many breeding projects pursued high yields, but nutrition was easily overlooked. Now research is paying more and more attention to both aspects. Scientists hope to select varieties that are both high-yield and nutritious, such as those with high protein content and trace elements such as iron and zinc (Voss-Fels et al., 2019; Hao et al., 2022). Some traditional varieties and wild wheat contain some useful genes that can improve nutrition or yield. Introducing these genes into modern wheat can make the new varieties more nutritious while ensuring that the yield does not decrease. This approach is very helpful in improving people's malnutrition problems.

4.2 Hybrid vigor of hybrid wheat and its quality traits

Hybrid wheat is to "match" two different wheat varieties to combine their respective advantages. The wheat bred in this way can not only have high yield, but also have better quality, such as more protein and stronger disease resistance (Zhao et al., 2015). But to breed good hybrid varieties, the most important thing is to choose the right "parents". Current genetic technology can help us analyze the effects of different combinations and improve the success rate. This method can select the most suitable combination and help cultivate high-quality wheat to meet people's demand for nutritious food.

4.3 Stress-resistant varieties with high-quality traits

In recent years, climate change has become more and more obvious. Extreme weather such as droughts and heat waves are increasing. Therefore, we need wheat that can grow well in this environment. This kind of wheat must not only be drought-resistant and heat-resistant, but also maintain good quality. Now breeders have added these "stress-resistant" genes to high-quality wheat (Mondal et al., 2016). They use some new technologies, such as genomic selection and high-throughput phenotyping technology (Paux et al., 2022), to find suitable breeding materials more quickly. The wheat bred in this way is not only nutritious, but also can be grown in different regions. They help improve food security and better cope with complex environments in the future.

5 Case Study: Regional Implementation of Fortified Wheat Varieties

5.1 Success in India in promoting zinc biofortified wheat

India has introduced zinc-enriched wheat varieties to reduce zinc deficiency. Zinc deficiency is a common health problem in India and neighboring countries. Farmers have helped wheat absorb more zinc by changing the way they apply fertilizers, such as using phosphorus-rich compost and zinc sulfate (Table 1). This method is called "biofortification". Studies have shown that it does increase the zinc content of wheat grains (Paramesh et al., 2020). This method not only makes wheat more nutritious, but also makes the soil healthier and the crops grow better. Therefore, it also helps promote more environmentally friendly agriculture (Sharma et al., 2019).

Table 1 Influence of integrated P management and Zn application on P concentration and uptake by wheat (average of 2 years) (Adopted from Paramesh et al., 2020)

Treatments	Grain P concentration (%)	Straw P concentration (%)	Grain P (kg/ha)	Straw P (kg/ha)	Total P (kg/ha)
Phosphorus levels					
Without P	0.28^{c}	0.13^{b}	10.4^{c}	7.6^{c}	17.9^{d}
P_{100}-F	0.3^{b}	0.13^{b}	13.5^{b}	8.2^{c}	21.7^{c}
P_{100}-PEC	0.38^{a}	0.15^{a}	18.1^{a}	10.5^{b}	28.6^{a}
P_{50}-PEC+P_{50}-F	0.37^{a}	0.15^{a}	18.0^{a}	11.0^{a}	29.0^{a}
P_{75}-PEC+VAM+PSB	0.38 a	0.15^{a}	17.3^{a}	10.2^{b}	27.4^{b}
Application of $ZnSO_4.7H_2O$					
Without Zn	0.34^{b}	0.15^{a}	13.9^{c}	9.1^{b}	23.0^{d}
25 kg-Soil	0.33^{b}	0.13^{c}	15.6^{b}	9.1^{b}	24.7^{c}
Two foliar **	0.36^{a}	0.15^{a}	15.4^{b}	9.8^{a}	25.2^{b}
Soil+Foliar *	0.36^{a}	0.14^{b}	16.9^{a}	10.0^{a}	26.9^{a}

Note: **-Two foliar spray at anthesis and one week after anthesis stage; *-one foliar spray at one week after anthesis stage. Similar letter in a column indicates non-significance difference between treatments (Adopted from Paramesh et al., 2020)

5.2 Ethiopia uses high-protein wheat in food aid programs
Ethiopia has introduced high-protein wheat in food aid programs to address malnutrition issues. This is particularly suitable for areas where wheat is the staple food. High-protein wheat provides more essential amino acids for the body, which helps improve nutrition. The local government selected varieties with high protein content and distributed this more nutritious wheat to those in need, such as children and pregnant women (Tanin et al., 2024). This example also shows that when breeding, we should not only focus on yield, but also pay attention to nutritional content, especially in areas in need of assistance.

5.3 China's innovation in wheat nutrigenomics
China has also made many new attempts in wheat breeding, with the goal of making wheat both nutritious and high-yielding. Researchers have proposed a method called "High Nutrient Use Efficiency Fertilization" (High NUFER). This method can make wheat have high yield and more protein, reduce fertilizer use, and have less impact on the environment (Hou et al., 2023). They developed the most suitable fertilization plan based on the genes and actual growth of wheat to help improve the nutritional level. These explorations in China show that as long as the method is appropriate, it is possible to cultivate high-yield and nutritious wheat, and it can also be more environmentally friendly, which will have a positive impact on food security.

6 Challenges and Opportunities
6.1 Genetic and physiological trade-offs
It is actually quite difficult to breed wheat that is both high-yielding and nutritious. Sometimes, in order to make wheat drought-resistant or disease-resistant, we may end up reducing its yield or affecting its quality. For example, some drought-resistant wheat may not produce much grain even though it is suitable for dry places. This is because these traits are not determined by a single gene, but by many genes and the environment (Bapela et al., 2022). Wheat genes are inherently complex. If you want it to be high-yielding, nutritious, disease-resistant and drought-resistant, it will be even more difficult (Mondal et al., 2016). Therefore, when breeding, you cannot just focus on one aspect. If you improve a certain trait, you may make others worse, so you have to try to balance it.

6.2 Socioeconomic and market constraints
In addition to technical issues, there are also some social and market difficulties. Some people do not approve of nutritionally fortified wheat, especially genetically modified wheat. When promoting it, you may encounter people who do not understand it and the policy does not keep up (Bhalla, 2006). The current market demand for wheat is more about how well it can be processed, such as how well it is ground into flour and how well it makes bread. On the contrary, whether it is nutritious is not the main consideration. This also makes it difficult to promote many varieties that focus on "nutrition" (Subedi et al., 2023). In addition, breeding and promoting new varieties cost a lot of money, which is a big problem for research on nutritious wheat (Saquee et al., 2024). To solve these problems, on the one hand, more publicity is needed to make people aware of the benefits of nutritious wheat; on the other hand, the government should also introduce policies and provide some financial and technical support.

6.3 Policy and research gap
The new technologies used in breeding, such as "genomic selection" and "marker-assisted breeding", are not widely used in practice. One reason is that policies cannot keep up and support is not strong enough (Paux et al., 2022). This affects the promotion speed of new technologies. In addition, whether fortified wheat is good for people if eaten for a long time has not been thoroughly studied. There are still many blanks in its impact on health and food security (Sharma et al., 2023). To solve these problems, scientists, governments and enterprises need to work together. Only through more communication and cooperation can we build a good mechanism to promote truly nutritious and promising wheat varieties so that more people can benefit from them.

7 Future Outlook
7.1 Integrating multi-omics technologies for nutritional breeding
Now, more and more scientists are beginning to use "multi-omics" to improve the nutrition of wheat. These methods include genome, transcriptome, proteome and metabolome. Through these technologies, we can

understand more clearly how wheat nutrition is formed, and we can also find out the key genes that affect nutrient accumulation and stress resistance (Li et al., 2021). With this information, breeders can select new varieties more directional. Such wheat is not only high in protein, but also rich in various trace elements. At the same time, its yield will not decrease, and its resistance will not deteriorate (Katamadze et al., 2023). These new tools can also help us breed wheat suitable for different regions to better meet people's nutritional needs.

7.2 Precision agriculture helps improve quality

Precision agriculture has been very popular in recent years. It uses some new technologies, such as remote sensing, soil monitoring and precision fertilization, to help farmers farm more scientifically. These technologies can make water and fertilizer use more accurately, avoid waste, and improve the quality of wheat (Yadav and Pyare, 2024). It can also monitor the growth of wheat at any time, such as whether there is a lack of water, fertilizer, or pests and diseases. If problems are found, farmers can take immediate measures to reduce losses and increase yields (Voss-Fels et al., 2019). If these precision agricultural technologies are combined with breeding technologies, high-yield and nutritious wheat can be grown, and damage to the environment can be reduced, making agriculture greener.

7.3 Global cooperation in wheat nutrition improvement

Breeding nutritious and resilient wheat is not something that one or two countries can do alone. This requires global cooperation. Countries can share seed resources, breeding techniques and research results. Only in this way can we breed wheat varieties suitable for planting in different places (Rajaram, 2001). Some international projects are already doing this. For example, BREEDWHEAT is a good example. It brings together scientists and breeders to study the nutrition and yield issues of wheat (Paux et al., 2022). Through such cooperation, scientists can breed nutritious and high-quality wheat varieties more quickly. These varieties can also be more easily promoted to different countries, which is very helpful for improving global food security and human health.

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Conflict of Interest Disclosure

The authors affirm 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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