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Cultivation of Specialty Wheats: Opportunities and Challenges

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Abstract This study explores the cultivation of specialty wheats, focusing on the opportunities and challenges they present. Specialty wheats, including ancient grains, colored wheats, gluten-free varieties, and high-nutritional wheats, offer advantages such as enhanced nutritional value, adaptability to specific environments, and meeting market demands. However, these varieties face challenges such as lower yields, limited market acceptance, and susceptibility to pests and diseases. The study discusses the potential of specialty wheats in organic agriculture and the functional food market, especially with the support of precision agriculture and genomic editing technologies, which can improve yields and environmental resilience. Additionally, low-input farming systems contribute to sustainable agriculture by reducing environmental footprints. The study suggests overcoming existing barriers through policy support, innovative breeding, and market strategies to promote the widespread cultivation and application of specialty wheats.

Keywords Specialty wheat; Sustainable agriculture; Genetic engineering; Climate change; Food security

1 Introduction

Specialty wheats refer to varieties of wheat that are cultivated for specific traits or uses, which may include enhanced nutritional content, unique flavors, or suitability for particular environmental conditions. These varieties are often developed through selective breeding or genetic modification to meet specific consumer demands or to adapt to challenging growing conditions. The scope of specialty wheats encompasses a wide range of applications, from health-focused products to sustainable agricultural practices, aiming to address both market needs and environmental challenges (Bhalla, 2006; Ying et al., 2019; Li et al., 2021).

Historically, wheat has been a cornerstone of global food security, contributing significantly to dietary calories and proteins worldwide. The Green Revolution marked a pivotal moment in wheat production, dramatically increasing yields and stabilizing food prices, which benefited both producers and consumers (Asseng et al., 2020). However, the demand for wheat continues to grow, particularly in developing regions, necessitating further innovations in wheat cultivation (Asseng et al., 2020).

Specialty wheats offer economic opportunities by catering to niche markets and potentially commanding higher prices due to their unique attributes. They also play a role in diversifying agricultural systems and enhancing resilience against biotic and abiotic stresses (Joshi et al., 2008; Chatrath et al., 2021; Bapela et al., 2022).

This review is to explore the opportunities and challenges associated with the cultivation of specialty wheats. This includes examining the potential of these varieties to contribute to sustainable agriculture, improve food security, and meet the evolving demands of consumers.

The review also aims to highlight the technological and genetic advancements that facilitate the development of specialty wheats, as well as the economic and environmental implications of their cultivation. Understanding these factors is crucial for stakeholders, including farmers, researchers, and policymakers, to make informed decisions that support the sustainable growth of the wheat industry.

2 Types of Specialty Wheats

2.1 Ancient grains

Ancient grains such as Einkorn, Emmer, and Spelt have gained renewed interest due to their unique nutritional profiles and potential health benefits. These grains are considered more resilient to certain environmental stresses compared to modern wheat varieties, which makes them attractive for cultivation in regions facing climate challenges. Their genetic diversity offers opportunities for breeding programs aimed at improving drought tolerance and disease resistance, which are critical in the face of global climate change (Li et al., 2021; Bapela et al., 2022).

However, the cultivation of ancient grains presents several challenges. These grains often have lower yields compared to modern wheat varieties, which can limit their economic viability for large-scale production. Additionally, the processing and marketing of ancient grains require specialized knowledge and infrastructure, which can be a barrier for farmers and producers. Despite these challenges, the growing consumer demand for diverse and nutritious food options provides a promising market for ancient grains (Chatrath et al., 2007; Shiferaw et al., 2013).

2.2 Colored wheats

Colored wheats, such as red, purple, and black varieties, are valued for their high antioxidant content, which is linked to various health benefits. These wheats contain anthocyanins and other phenolic compounds that contribute to their distinctive colors and potential health-promoting properties. The cultivation of colored wheats can be an opportunity to diversify agricultural products and meet the increasing consumer demand for functional foods (Bhalla, 2006; Asseng et al., 2020).

Despite their benefits, colored wheats face challenges in terms of agronomic performance and market acceptance. These varieties may require specific growing conditions to achieve optimal color and nutritional quality, which can limit their adaptability to different environments. Additionally, consumer awareness and acceptance of colored wheats are still developing, which can affect market penetration. Efforts to educate consumers and promote the health benefits of colored wheats are essential to overcoming these challenges (Joshi et al., 2007; Li et al., 2021).

2.3 Gluten-free varieties

Gluten-free varieties such as Teff and Kamut are increasingly popular due to the rising prevalence of gluten-related disorders and the growing demand for gluten-free products. Teff, in particular, is a nutrient-dense grain that is rich in protein, fiber, and essential minerals, making it an attractive option for health-conscious consumers. These grains can be used in blends to create gluten-free products that cater to a wider audience (Bhalla, 2006; Ying et al., 2019).

However, the production of gluten-free grains poses several challenges. The cultivation of these grains may require different agronomic practices compared to traditional wheat, which can increase production costs. Additionally, the gluten-free market is highly competitive, and producers must ensure that their products meet strict quality and safety standards. Despite these challenges, the expanding gluten-free market offers significant opportunities for producers willing to invest in these specialty grains (Chatrath et al., 2007; Shiferaw et al., 2013).

2.4 High-nutritional wheats

High-nutritional wheats, including high-protein and low-glycemic index (GI) varieties, are developed to meet the growing demand for healthier food options. These wheats are bred to enhance specific nutritional attributes, such as increased protein content and reduced carbohydrate impact on blood sugar levels. The development of such varieties aligns with global health trends and offers opportunities for improving dietary quality (Joshi et al., 2007; Asseng et al., 2020).

The cultivation of high-nutritional wheats involves challenges related to breeding and market acceptance. Developing these varieties requires advanced breeding techniques and a deep understanding of genetic traits, which can be resource-intensive. Additionally, consumer education is crucial to highlight the benefits of high-nutritional wheats and drive market demand. Despite these challenges, the potential health benefits and market opportunities make high-nutritional wheats a promising area for future agricultural innovation (Li et al., 2021; Bapela et al., 2022).

3 Opportunities in Wheat Cultivation

3.1 Market trends and consumer demand

The increasing consumer interest in functional foods presents a significant opportunity for specialty wheat cultivation. Functional foods, which offer health benefits beyond basic nutrition, are gaining popularity as consumers become more health-conscious. This trend is driving demand for wheat varieties that are rich in nutrients and have specific health benefits, such as high fiber content or antioxidant properties (Chatrath et al., 2007; Shiferaw et al., 2013).

The organic and sustainable food movements are also creating opportunities for specialty wheats. Consumers are increasingly seeking products that are produced sustainably and organically, which aligns with the cultivation of specialty wheats that often require less intensive chemical inputs. This shift in consumer preferences supports the development of wheat varieties that are better suited for organic farming practices, thereby opening new market segments for farmers (Chatrath et al., 2007; Shiferaw et al., 2013).

3.2 Economic and trade benefits

Specialty wheats have significant export potential due to their unique qualities and the premium prices they can command in international markets. Countries that can produce high-quality specialty wheats have the opportunity to tap into niche markets abroad, where consumers are willing to pay more for distinctive wheat products. This can lead to increased revenue for farmers and contribute to the economic growth of wheat-producing regions (Chatrath et al., 2007; Shiferaw et al., 2013).

The rise of artisanal baking and brewing industries has created niche markets for specialty wheats. These industries often seek unique wheat varieties that offer distinct flavors and textures, which are essential for crafting high-quality artisanal products. By cultivating specialty wheats, farmers can cater to these niche markets, thereby diversifying their income streams and reducing reliance on traditional wheat markets (Chatrath et al., 2007; Shiferaw et al., 2013).

3.3 Genetic and agronomic advancements

Advancements in genetic and agronomic research offer opportunities to breed specialty wheats that are both high-yielding and resilient to environmental stresses. Newer wheat varieties have been developed to produce more grain while reducing nitrogen emissions, which is crucial for sustainable agriculture (Bhalla, 2006; Ying et al., 2019; Bapela et al., 2022). These advancements can help meet the growing demand for wheat while minimizing environmental impact.

The development of diverse wheat varieties through genetic improvement and breeding techniques provides an opportunity for crop diversification. This diversification can enhance food security by reducing dependency on a limited number of wheat varieties and increasing resilience to climate change and other agricultural challenges (Li et al., 2021; Bapela et al., 2022). By exploring the genetic potential of wheat, farmers can cultivate a wider range of specialty wheats that meet specific market demands and environmental conditions.

4 Agronomic and Environmental Challenges

4.1 Adaptation to diverse climates

The cultivation of specialty wheats faces significant challenges in adapting to diverse climatic conditions. Climate change has introduced a range of abiotic stresses, such as drought and extreme temperatures, which threaten wheat production globally. The genetic improvement of wheat for drought tolerance is crucial, as recurrent droughts can severely impact yield. Breeding programs have focused on developing drought-tolerant varieties by exploiting genetic variation and understanding the physiological and biochemical mechanisms that contribute to drought resilience (Table 1) (Bapela et al., 2022; Trono and Pecchioni, 2022). However, the adaptation of specialty wheats to diverse climates remains a complex task due to the variability in environmental conditions and the need for specific genetic traits that confer resilience (Beres et al., 2022).

Table 1 Impact of drought stress on agro-physiological traits in wheat (Adopted from Bapela et al., 2022)

Agronomic Trait	Reduction (%)	Location/Country
Plant height	34.45%	Pakistan
Number of tillers per plant	25.43%	
Grains per spike	38.10%	
Grain yield	62.75%	
1000-grain weight	19.42%	
Biomass	27.05%	China
Grain yield	25%	
Grain numbers per spike	48%	Kansas State University, USA
Individual grain weight [mg]	35%	
Leaf photosynthetic rate	32%	
Chlorophyllcontent	19%	
Spikelet fertility	29%	
Plantheight	14.7%	Egypt
Days to 50% heading	4.78	
Number of effective tillers	36.3%	
Spike length	23.7%	
1000-grain weight	16.4%	
Grain yield	43.2%	
Biomass	32.9%	
Harvest index	12.7%	
Number of grains perspike	50%	South Africa
Root bimass	23%	South Africa
Grainyield	40%	SouthAfrica
Above-ground biomass	45%	Colorado State University, USA
Leaf water content (LWC) in cultivars Seri	64.9%	Philippines
M82 and Weebil4,respectively	73.8%	
LWC in cultivars Kukriand	72.6%~54.4%	Australia
Excalibur, respectively	74.5%~50.5%	

Moreover, the adaptation of specialty wheats to different climates is further complicated by the need to balance yield potential with environmental sustainability. While modern breeding techniques have improved yield potential, they often require specific environmental conditions to achieve optimal results. For instance, durum wheat, widely cultivated in the Mediterranean, faces challenges due to its reliance on genetically uniform varieties that are less resistant to environmental stress (Licaj et al., 2023). Therefore, there is a need for innovative breeding strategies that incorporate genetic diversity to enhance the adaptability of specialty wheats to a range of climatic conditions (Mondal et al., 2016; Fellahi et al., 2024).

4.2 Pest and disease susceptibility

Specialty wheats are often more susceptible to pests and diseases compared to conventional varieties, posing a significant challenge to their cultivation. The genetic diversity within wheat species offers potential for improving resistance to diseases and pests, but the process of incorporating these traits into specialty wheats is time-consuming and complex (Mondal et al., 2016). For example, Khorasan wheat, a type of ancient wheat, exhibits high susceptibility to powdery mildew and other fungal diseases, making it more suitable for organic farming systems where chemical control is limited (Grausgruber et al., 2005). This susceptibility necessitates the development of integrated pest management strategies that can effectively mitigate these risks while maintaining the integrity of specialty wheat production.

The management of pest and disease susceptibility in specialty wheats also requires a comprehensive understanding of the interactions between genotype, environment, and management practices. The development of resistant cultivars is lagging, particularly for serious threats like Fusarium head blight, which affects durum wheat (Beres et al., 2022). Advances in genetic engineering and breeding techniques, such as the use of cisgenic methods and CRISPR/Cas9 tools, offer promising avenues for enhancing disease resistance in specialty wheats (Trono and Pecchioni, 2022). However, these technologies must be integrated into broader agronomic systems to ensure sustainable production and minimize the impact of pests and diseases (O'Leary et al., 2018).

4.3 Yield and economic viability

The yield and economic viability of specialty wheats are critical factors that influence their cultivation. Specialty wheats often have lower yields compared to modern wheat varieties, which can limit their economic attractiveness to farmers. For instance, Khorasan wheat yields significantly less than modern durum wheats, which poses a challenge for its widespread adoption (Grausgruber et al., 2005). Despite this, specialty wheats offer unique market opportunities due to their nutritional and organoleptic qualities, which can command premium prices in niche markets (Grausgruber et al., 2005). Therefore, balancing yield with market demand is essential for the economic viability of specialty wheats.

Economic viability is also influenced by the cost of production and the ability to compete with conventional wheat varieties. While vertical farming offers a potential solution to increase wheat yields by optimizing growing conditions, the high energy and capital costs associated with this method make it economically uncompetitive with current market prices (Asseng et al., 2020). Therefore, improving the economic viability of specialty wheats requires a multifaceted approach that includes optimizing agronomic practices, enhancing genetic traits for yield improvement, and developing market strategies that capitalize on the unique attributes of specialty wheats (Ying et al., 2019; Fellahi et al., 2024).

5 Market and Policy Barriers

5.1 Lack of awareness among farmers and consumers

A significant barrier to the cultivation of specialty wheats is the lack of awareness among both farmers and consumers. Farmers often remain uninformed about the potential benefits and market opportunities associated with specialty wheats, which can lead to low adoption rates. This lack of awareness is compounded by insufficient extension services and limited access to information, which are crucial for educating farmers about new agricultural technologies and practices (Yigezu et al., 2021). Additionally, consumers may not be fully aware of the nutritional and culinary benefits of specialty wheats, which can limit market demand and discourage farmers from diversifying their crops (Mamine and Farès, 2020).

Efforts to increase awareness must focus on both ends of the supply chain. For farmers, this could involve enhanced extension services and training programs that highlight the economic and environmental benefits of specialty wheats. For consumers, marketing campaigns and educational initiatives can help to build demand by emphasizing the unique qualities and health benefits of these grains. Bridging this awareness gap is essential for fostering a supportive market environment that encourages the cultivation and consumption of specialty wheats (Chatrath et al., 2007; Mamine and Farès, 2020).

5.2 Regulatory challenges in seed certification

Regulatory challenges in seed certification present another significant barrier to the cultivation of specialty wheats. Stringent and often outdated seed certification processes can hinder the introduction and adoption of new wheat varieties. In some regions, the imbalance of power among actors in the seed sector and ill-conceived variety licensing contracts further complicate access to seeds of newly released varieties (Yigezu et al., 2021). These regulatory hurdles can delay the availability of improved seeds to farmers, thereby slowing the diffusion of innovative agricultural practices (Yigezu et al., 2021).

To overcome these challenges, there is a need for policy reforms that streamline seed certification processes and promote transparency and fairness in seed licensing. Encouraging private sector engagement in seed multiplication and revising variety testing procedures can also facilitate the introduction of new specialty wheat varieties. Such reforms would not only enhance the availability of high-quality seeds but also support the broader adoption of specialty wheats by reducing bureaucratic obstacles (Joshi et al., 2007; Yigezu et al., 2021).

5.3 Difficulties in marketing and supply chain integration

Marketing and supply chain integration pose significant challenges for the cultivation of specialty wheats. The lack of a well-structured value chain can impede the efficient distribution and marketing of these crops. Technical issues such as varietal selection, crop management, and storage, along with economic factors like cost and market opportunities, contribute to the slow adoption and dissemination of specialty wheats (Mamine and Farès, 2020). These challenges are exacerbated by the absence of robust market linkages and contracting mechanisms that can ensure fair pricing and reliable demand for farmers (Mamine and Farès, 2020).

Addressing these difficulties requires a coordinated effort to develop a comprehensive value chain that supports the production, processing, and marketing of specialty wheats. This includes fostering partnerships between farmers, processors, and retailers to create a more integrated supply chain. Additionally, leveraging competitive advantages such as superior product quality and ecosystem benefits can help to position specialty wheats more favorably in the market. By focusing on these areas, stakeholders can enhance the marketability and profitability of specialty wheats, encouraging greater adoption among farmers (Mamine and Farès, 2020).

6 Sustainability and Environmental Benefits

6.1 Potential for low-input farming systems

Specialty wheats, such as spelt and bread wheat landraces, offer significant potential for low-input farming systems. These varieties are well-suited to environments with minimal nitrogen inputs, as they can maintain productivity and quality even under marginal soil conditions. Spelt wheat, for instance, has been identified as a viable alternative to common wheat in low nitrogen input systems, demonstrating resilience and adaptability in both low-quality and fertile soils (Figure 1) (Sugár et al., 2019). Similarly, bread wheat landraces have shown adaptability to low-input and organic environments, providing a valuable genetic resource for breeding programs aimed at enhancing productivity in such systems (Korpetis et al., 2023).

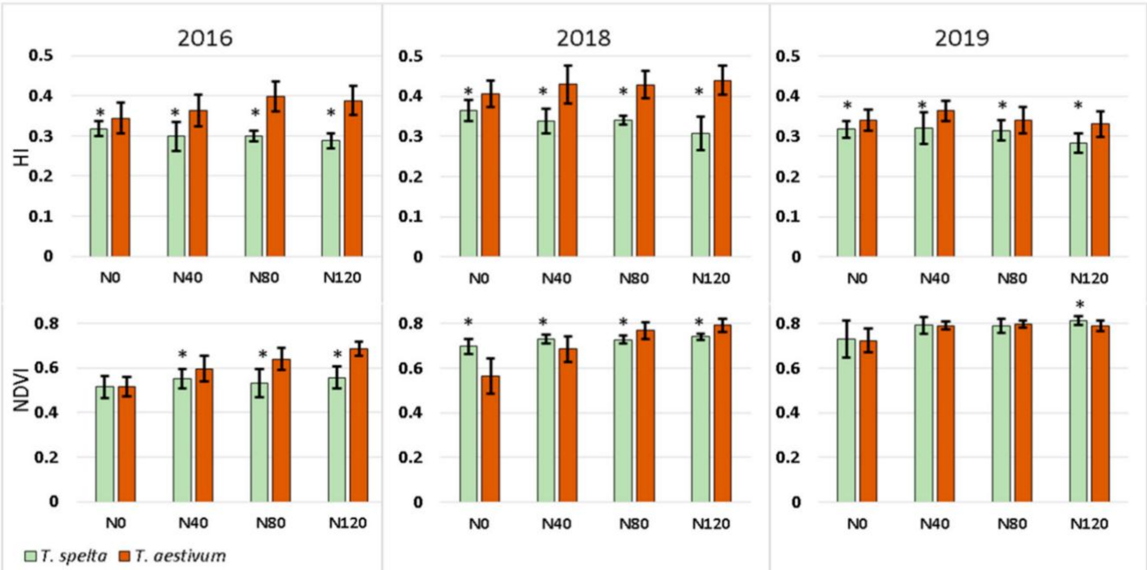

Figure 1 Harvest Index (HI) and NDVI of spelt (*T. spelta*) and common wheat (*T. aestivum*) across varieties under four different nitrogen fertilisation treatments (0, 40 kg N ha^{-1}, 80 kg N ha^{-1} and 120 kg N ha^{-1}) at Martonvásár (Hungary) in 2016, 2018 and 2019 (Adopted from Sugár et al., 2019)

Image caption: * indicates statistically significant difference between spelt and common wheat (Adopted from Sugár et al., 2019)

The cultivation of specialty wheats in low-input systems not only supports sustainable agriculture but also reduces the environmental footprint associated with high-input farming. By minimizing the need for synthetic fertilizers and other inputs, these systems can decrease greenhouse gas emissions and other environmental impacts. For example, the use of compost in dryland wheat cultivation has been shown to improve yield while reducing negative environmental indicators, such as impacts on human health and ecosystem quality (Amirahmadi et al., 2024). This approach aligns with the goals of sustainable agriculture by promoting resource efficiency and environmental conservation.

6.2 Contribution to agro-biodiversity conservation

Specialty wheats play a crucial role in conserving agro-biodiversity, which is essential for resilient and sustainable agricultural systems. The cultivation of diverse wheat varieties, including landraces and ancient grains, helps maintain genetic diversity within agricultural landscapes. This diversity is vital for breeding programs that aim to develop crops with improved resistance to diseases, pests, and changing climatic conditions (Korpetis et al., 2023; Zhong, 2024). By preserving a wide range of genetic traits, specialty wheats contribute to the overall stability and adaptability of agricultural systems.

Moreover, the promotion of agro-biodiversity through the cultivation of specialty wheats can mitigate the erosion of genetic resources that has occurred with the widespread adoption of high-yielding commercial cultivars. The reintroduction and cultivation of landraces, for example, can expand the genetic base of cultivated wheat, providing a buffer against environmental stresses and enhancing the resilience of cropping systems (Korpetis et al., 2023). This approach not only supports biodiversity conservation but also aligns with sustainable intensification strategies that seek to balance productivity with environmental stewardship (Shiferaw et al., 2013).

6.3 Role in carbon sequestration and soil health improvement

The cultivation of specialty wheats can significantly contribute to carbon sequestration and the improvement of soil health. Practices such as surface seeding and the use of compost in wheat cultivation have been shown to enhance soil organic carbon levels and improve soil structure. Surface seeding, for instance, increases soil organic carbon and improves soil aggregation, which are critical for maintaining soil health and fertility (Singh et al., 2022). These practices also reduce the carbon footprint of wheat production by minimizing soil disturbance and promoting carbon storage in the soil.

In addition to carbon sequestration, specialty wheats can improve soil health by enhancing nutrient cycling and reducing the reliance on synthetic fertilizers. The integration of compost in wheat cultivation, particularly in dryland systems, has been demonstrated to improve yield while reducing environmental impacts, such as greenhouse gas emissions and resource depletion (Amirahmadi et al., 2024). By fostering healthier soils, specialty wheats support sustainable agricultural practices that enhance long-term productivity and environmental resilience. This approach aligns with the broader goals of ecological intensification, which seeks to optimize agricultural outputs while minimizing negative environmental impacts (Cassman, 1999).

7 Technological and Research Developments

7.1 Advances in genomic tools for specialty wheat breeding

Recent advancements in genomic tools have significantly enhanced the breeding of specialty wheats by enabling more precise and efficient selection processes. High-throughput genomic tools, such as single nucleotide polymorphism (SNP) arrays and high-density molecular marker maps, have been developed to facilitate genome-wide association studies (GWAS) and genomic selection. These tools allow breeders to efficiently analyze genetic diversity and identify genomic regions associated with important agronomic traits, such as disease resistance and stress tolerance (Rasheed and Xia, 2019; Paux et al., 2022). The integration of these genomic tools into breeding programs has accelerated the development of wheat varieties with improved yield and quality, addressing the challenges posed by climate change and increasing global food demands (Mondal et al., 2016; Li et al., 2021).

Moreover, the use of genome editing technologies, such as CRISPR, has opened new avenues for functional genomics and genetic improvement in wheat. These technologies enable precise modifications of the wheat genome, allowing for the introduction of beneficial traits without the need for traditional cross-breeding methods. This is particularly important for overcoming the complexities associated with the hexaploid wheat genome, which has historically impeded genetic research and breeding efforts (Li et al., 2021; Subedi et al., 2023). The combination of genome editing with other molecular breeding strategies promises to further enhance the genetic improvement of specialty wheats, ensuring their resilience and productivity in diverse environmental conditions (Banka et al., 2024; Zhang et al., 2024).

7.2 Role of precision agriculture in enhancing cultivation

Precision agriculture plays a crucial role in enhancing the cultivation of specialty wheats by optimizing resource use and improving crop management practices. The application of precision agriculture technologies, such as remote sensing, GPS-guided equipment, and data analytics, allows for the precise monitoring and management of wheat fields. These technologies enable farmers to apply inputs like water, fertilizers, and pesticides more efficiently, reducing waste and minimizing environmental impact (Bhalla, 2006; Li et al., 2021). By tailoring agricultural practices to the specific needs of each field, precision agriculture helps maximize yield and quality, which is essential for meeting the growing demand for specialty wheat products (Paux et al., 2022; Haugrud et al., 2024).

Furthermore, precision agriculture supports the integration of advanced breeding techniques by providing detailed phenotypic data that can be used in genomic selection and breeding programs. High-throughput phenotyping platforms, which are a component of precision agriculture, allow for the rapid assessment of plant traits under various environmental conditions. This data is invaluable for breeders aiming to develop wheat varieties that are not only high-yielding but also resilient to biotic and abiotic stresses (Mondal et al., 2016; Li et al., 2021). The synergy between precision agriculture and genomic tools is pivotal in advancing the cultivation of specialty wheats, ensuring sustainable production in the face of global challenges (Brinton et al., 2020).

7.3 Development of value-added products

The development of value-added products from specialty wheats is a growing area of interest, driven by consumer demand for diverse and nutritious food options. Advances in genomics and breeding have facilitated the creation of wheat varieties with enhanced nutritional profiles, such as increased levels of essential vitamins and minerals. These biofortified wheats can be used to produce a range of value-added products, including health-focused foods and functional ingredients, which cater to the evolving dietary preferences of consumers (Subedi et al., 2023; Banka et al., 2024). The ability to tailor wheat varieties for specific end-use qualities, such as baking and milling, further expands the potential for developing innovative products that meet market demands (Brinton et al., 2020).

In addition to nutritional enhancements, the development of value-added products also involves improving the processing qualities of wheat. Genomic tools have enabled the identification of genetic loci associated with key processing traits, allowing breeders to select for wheat varieties that perform well in industrial applications. This includes traits such as dough strength and elasticity, which are critical for producing high-quality bread and pasta products (Kumar et al., 2022; Subedi et al., 2023). By focusing on both nutritional and processing attributes, the development of value-added products from specialty wheats not only adds economic value but also contributes to food security and sustainability by promoting the use of diverse wheat varieties (Haugrud et al., 2024).

8 Future Directions and Recommendations

8.1 Integrating specialty wheats into mainstream agriculture

Integrating specialty wheats into mainstream agriculture requires a multifaceted approach that includes the adoption of advanced breeding techniques and sustainable farming practices. The development of newer wheat varieties that produce higher yields while reducing nitrogen emissions is a promising step towards sustainable agriculture. These varieties have shown potential in reducing nitrogen losses significantly, which is crucial for minimizing environmental impact while maintaining high productivity (Ying et al., 2019). Additionally, the use of genome-editing technologies and other advanced breeding methods can facilitate the development of elite wheat cultivars that are resilient to climate change and other environmental stresses, thereby supporting their integration into mainstream agriculture (Li et al., 2021).

Moreover, the successful integration of specialty wheats into mainstream agriculture will depend on overcoming challenges such as biotic and abiotic stresses, which are prevalent in regions like South Asia. Addressing these challenges through genetic improvements and better agronomic practices can help break yield barriers and improve the resilience of wheat crops. Strengthening international collaborations, such as those with CIMMYT, can also play a vital role in developing more productive and sustainable wheat genotypes (Chatrath et al., 2007; Joshi et al., 2007). By focusing on these strategies, specialty wheats can be effectively integrated into existing agricultural systems, contributing to global food security.

8.2 Policy Support for Specialty Crop Farmers

Policy support is crucial for the successful cultivation and marketability of specialty wheats. Governments and agricultural bodies need to implement policies that provide financial incentives and technical support to farmers adopting specialty crops. This includes subsidies for adopting advanced technologies and practices that enhance yield and reduce environmental impact, such as those demonstrated in the development of drought-tolerant wheat varieties (Bapela et al., 2022). Additionally, policies should focus on improving infrastructure and market access for specialty crop farmers, ensuring they can compete effectively in the global market (Shiferaw et al., 2023).

Furthermore, policy frameworks should encourage research and development in the field of specialty wheats, promoting innovations that can lead to sustainable intensification of wheat production. This includes supporting initiatives that aim to reduce the environmental footprint of wheat farming through the use of cutting-edge technologies and sustainable practices (Li et al., 2021). By fostering an environment that supports innovation and sustainability, policy measures can significantly enhance the viability and profitability of specialty wheat cultivation.

8.3 Research priorities for enhancing cultivation and marketability

Research priorities for enhancing the cultivation and marketability of specialty wheats should focus on developing varieties that meet specific quality and resilience criteria. This includes the use of genomics-assisted breeding to improve end-use quality traits, such as milling and baking qualities, which are essential for meeting the demands of millers and bakers in the international market (Subedi et al., 2023). Additionally, research should aim to identify and utilize genetic variations that confer drought tolerance and other stress resistances, thereby improving the adaptability of wheat to diverse environmental conditions (Bapela et al., 2022).

Another critical area of research is the exploration of innovative farming systems, such as vertical farming, which can significantly increase wheat yields while minimizing land use and environmental impact. Although currently not economically competitive, vertical farming presents a potential future direction for wheat production, especially in regions facing climate challenges (Asseng et al., 2020). By prioritizing these research areas, the cultivation and marketability of specialty wheats can be significantly enhanced, contributing to a more sustainable and resilient agricultural sector.

9 Concluding Remarks

The cultivation of specialty wheats presents numerous opportunities and challenges in modern agriculture. On the opportunity side, specialty wheats can contribute significantly to food security and sustainable agricultural practices. They offer the potential for higher yields and improved environmental outcomes when integrated with eco-friendly agricultural practices, such as compost fertilization and crop rotation, which have been shown to enhance yield stability and reduce environmental impacts. Additionally, genetic engineering and breeding innovations provide avenues to develop wheat varieties with enhanced tolerance to abiotic stresses like drought and salinity, which are crucial for maintaining productivity in the face of climate change.

However, challenges remain, particularly in terms of environmental sustainability and resource management. The environmental impacts of wheat production, such as greenhouse gas emissions and resource depletion, need to be addressed through sustainable practices and life cycle assessments. Moreover, the stagnation of wheat yields in certain regions, such as South Asia, highlights the need for continued research and development to overcome biotic and abiotic stresses and improve total factor productivity. The integration of innovative agricultural practices and technologies is essential to meet these challenges and ensure the long-term viability of specialty wheat cultivation.

Specialty wheats hold strategic importance in modern agriculture due to their potential to enhance food security and support sustainable development. As a staple crop, wheat contributes significantly to global dietary needs, providing essential carbohydrates and proteins. The development of specialty wheats tailored to specific regional needs can promote agricultural innovation and economic growth, offering farmers opportunities for better income and improved livelihoods. These crops can also play a crucial role in diversifying agricultural systems and enhancing resilience against climate change and market fluctuations.

Furthermore, the strategic importance of specialty wheats is underscored by their role in international trade and food security initiatives. The global wheat research community, through collaborations like the Wheat Initiative, is focused on addressing production challenges and ensuring that wheat can meet future demand despite environmental and economic pressures. By investing in research and innovation, and by adopting sustainable intensification practices, the agricultural sector can harness the full potential of specialty wheats to contribute to a more secure and sustainable food system.

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References

Amirahmadi E., Ghorbani M., Moudrý J., Bernas J., Mukosha C., and Hoang T., 2024, Environmental assessment of dryland and irrigated winter wheat cultivation under compost fertilization strategies, Plants, 13(4): 509.
https://doi.org/10.3390/plants13040509

Asseng S., Guarin J., Raman M., Monje O., Kiss G., Despommier D., Meggers F., and Gauthier P., 2020, Wheat yield potential in controlled-environment vertical farms, Proceedings of the National Academy of Sciences of the United States of America, 117: 19131-19135.
https://doi.org/10.1073/pnas.2002655117

Banka V., Pheirim R., and Waghmode P., 2024, Genomic innovations in wheat (*Triticum aestivum* L.): a comprehensive review of recent developments and future directions, Journal of Advances in Biology and Biotechnology, 27(9): 795-806.
https://doi.org/10.9734/jabb/2024/v27i91353

Bapela T., Shimelis H., Tsilo T., and Mathew I., 2022, Genetic improvement of wheat for drought tolerance: progress, challenges and opportunities, Plants, 11(10): 1331.
https://doi.org/10.3390/plants11101331

Beres B., Rahmani E., Clarke J., Grassini P., Pozniak C., Geddes C., Porker K., May W., and Ransom J., 2020, A systematic review of durum wheat: enhancing production systems by exploring genotype, environment, and management (G×E×M) synergies, Frontiers in Plant Science, 11: 568657.
https://doi.org/10.3389/fpls.2020.568657

Bhalla P., 2006, Genetic engineering of wheat--current challenges and opportunities, Trends in Biotechnology, 24(7): 305-311.
https://doi.org/10.1016/J.TIBTECH.2006.04.008

Brinton J., Ramirez-Gonzalez R., Simmonds J., Wingen L., Orford S., Griffiths S., Haberer G., Spannagl M., Walkowiak S., Pozniak C., and Uauy C., 2020, A haplotype-led approach to increase the precision of wheat breeding, Communications Biology, 3: 712.
https://doi.org/10.1038/s42003-020-01413-2

Cassman K., 1999, Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture, Proceedings of the National Academy of Sciences of the United States of America, 96(11): 5952-5959.
https://doi.org/10.1073/PNAS.96.11.5952

Chatrath R., Mishra B., Ferrara G., Singh S., and Joshi A., 2007, Challenges to wheat production in South Asia, Euphytica, 157: 447-456.
https://doi.org/10.1007/s10681-007-9515-2

Fellahi Z., Boubellouta T., Hannachi A., Belguet H., Louahdi N., Benmahammed A., Utkina A., and Rebouh N., 2024, Exploitation of the genetic variability of diverse metric traits of durum wheat (*Triticum turgidum* L. ssp. *durum* Desf.) cultivars for local adaptation to semi-arid regions of Algeria, Plants, 13(7): 934.
https://doi.org/10.3390/plants13070934

Grausgruber H., Oberforster M., Ghambashidze G., and Ruckenbauer P., 2005, Yield and agronomic traits of Khorasan wheat (*Triticum turanicum* Jakubz.), Field Crops Research, 91: 319-327.
https://doi.org/10.1016/J.FCR.2004.08.001

Haugrud A., Achilli A., Martínez-Peña R., and Klymiuk V., 2024, Future of durum wheat research and breeding: insights from early career researchers, The Plant Genome, 18(1): e20453.
https://doi.org/10.1002/tpg2.20453

Joshi A., Mishra B., Chatrath R., Ferrara G., and Singh R., 2007, Wheat improvement in India: present status, emerging challenges and future prospects, Euphytica, 157: 431-446.
https://doi.org/10.1007/s10681-007-9385-7

Korpetis E., Ninou E., Mylonas I., Ouzounidou G., Xynias I., and Mavromatis A., 2023, Bread wheat landraces adaptability to low-input agriculture, Plants, 12(13): 2561.
https://doi.org/10.3390/plants12132561

Kumar S., Jacob S., Mir R., Vikas V., Kulwal P., Chandra T., Kaur S., Kumar U., Kumar S., Sharma S., Singh R., Prasad S., Singh A., Singh A., Kumari J., Saharan M., Bhardwaj S., Prasad M., Kalia S., and Singh K., 2022, Indian wheat genomics initiative for harnessing the potential of wheat germplasm resources for breeding disease-resistant, Nutrient-dense, and climate-resilient cultivars, Frontiers in Genetics, 13: 834366.
https://doi.org/10.3389/fgene.2022.834366

Li S., Zhang C., Li J., Yan L., Wang N., and Xia L., 2021, Present and future prospects for wheat improvement through genome editing and advanced technologies, Plant Communications, 2(4): 100211.
https://doi.org/10.1016/j.xplc.2021.100211

Licaj I., Di Meo M., Fiorillo A., Samperna S., Marra M., and Rocco M., 2023, Comparative analysis of the response to polyethylene glycol-simulated drought stress in roots from seedlings of “modern” and “ancient” wheat varieties, Plants, 12(3): 428.
https://doi.org/10.3390/plants12030428

Mamine F., and Farès M., 2020, Barriers and levers to developing wheat-pea intercropping in Europe: a review, Sustainability, 12(17): 6962.
https://doi.org/10.3390/su12176962

Mondal S., Rutkoski J., Velu G., Singh P., Crespo-Herrera L., Guzmán C., Bhavani S., Lan C., He X., and Singh R., 2016, Harnessing diversity in wheat to enhance grain yield, climate resilience, disease and insect pest resistance and nutrition through conventional and modern breeding approaches, Frontiers in Plant Science, 7: 991.
https://doi.org/10.3389/fpls.2016.00991

O'Leary G., Aggarwal P., Calderini D., Connor D., Craufurd P., Eigenbrode S., Han X., and Hatfield J., 2018, Challenges and responses to ongoing and projected climate change for dryland cereal production systems throughout the world, Agronomy, 8(4): 34.
https://doi.org/10.3390/AGRONOMY8040034

Paux E., Lafarge S., Balfourier F., Derory J., Charmet G., Alaux M., Perchet G., Bondoux M., Baret F., Barillot R., Ravel C., Sourdille P., Gouis L., and Consortium O., 2022, Breeding for economically and environmentally sustainable wheat varieties: an integrated approach from genomics to selection, Biology, 11(1): 149.
https://doi.org/10.3390/biology11010149

Rasheed A., and Xia X., 2019, From markers to genome-based breeding in wheat, Theoretical and Applied Genetics, 132: 767-784.
https://doi.org/10.1007/s00122-019-03286-4

Shiferaw B., Smale M., Braun H., Duveiller E., Reynolds M., and Muricho G., 2013, Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security, Food Security, 5: 291-317.
https://doi.org/10.1007/s12571-013-0263-y

Singh S., Patra A., Chand R., Jatav H., Luo Y., Rajput V., Sehar S., Attar S., Khan M., Jatav S., Minkina T., and Adil M., 2022, Surface seeding of wheat: a sustainable way towards climate resilience agriculture, Sustainability, 14(12): 7460.
https://doi.org/10.3390/su14127460

Subedi M., Ghimire B., Bagwell J., Buck J., and Mergoum M., 2023, Wheat end-use quality: state of art, genetics, genomics-assisted improvement, future challenges, and opportunities, Frontiers in Genetics, 13: 1032601.
https://doi.org/10.3389/fgene.2022.1032601

Sugár E., Fodor N., Sándor R., Bónis P., Vida G., and Árendás T., 2019, Spelt wheat: an alternative for sustainable plant production at low n-levels, Sustainability, 11(23): 6726.
https://doi.org/10.3390/su11236726

Timsina J., and Connor D., 2001, Productivity and management of rice-wheat cropping systems: issues and challenges, Field Crops Research, 69: 93-132.
https://doi.org/10.1016/S0378-4290(00)00143-X

Trono D., and Pecchioni N., 2022, Candidate genes associated with abiotic stress response in plants as tools to engineer tolerance to drought, salinity and extreme temperatures in wheat: an overview, Plants, 11(23): 3358.
https://doi.org/10.3390/plants11233358

Yigezu Y., Bishaw Z., Niane A., Alwang J., El-Shater T., Boughlala M., Aw-Hassan A., Tadesse W., Bassi F., Amri A., and Baum M., 2021, Institutional and farm-level challenges limiting the diffusion of new varieties from public and CGIAR centers: the case of wheat in Morocco, Food Security, 13: 1359-1377.
https://doi.org/10.1007/s12571-021-01191-7

Ying H., Yin Y., Zheng H., Wang Y., Zhang Q., Xue Y., Stefanovski D., Cui Z., and Dou Z., 2019, Newer and select maize, wheat, and rice varieties can help mitigate N footprint while producing more grain, Global Change Biology, 25: 4273-4281.
https://doi.org/10.1111/gcb.14798

Zhang B.C., Zhu J.H., Fan M., Wang W.D., and Hua W., 2024, Utilizing high-throughput phenotyping for disease resistance in wheat, Molecular Plant Breeding, 15(5): 233-246.
https://doi.org/10.5376/mpb.2024.15.0023

Zhong J.L., 2024, Discovering genes that enhance yield in drought conditions within turkish winter wheat, Triticeae Genomics and Genetics, 15(3): 121-124.
https://doi.org/10.5376/tgg.2024.15.0012