Field Crop 2024, Vol.7, No.4, 201-211
http://cropscipublisher.com/index.php/fc

Research Report Open Access

Comparative Analysis of Triticale and Wheat: Yield, Adaptability, and Nutritional Content

Rugang Xu, Qiuxia Sun
Modern Agricultural Research Center, Cuixi Academy of Biotechnology, Zhuji, 311800, China
Corresponding author: qiuxia.sun@cuixi.org
Field Crop, 2024, Vol.7, No.4 doi: 10.5376/fc.2024.07.0020
Received: 11 May, 2024
Accepted: 23 Jun., 2024
Published: 14 Jul., 2024

Preferred citation for this article:
Xu R.G., and Sun Q.X., 2024, Comparative analysis of triticale and wheat: yield, adaptability, and nutritional content, Field Crop, 7(4): 201-211 (doi: 10.5376/fc.2024.07.0020)

Abstract This study aims to provide a comprehensive comparison between triticale and wheat in terms of their yield performance, adaptability to various environmental conditions, and nutritional content. Triticale, a hybrid of wheat and rye, has shown promising results in several studies, often outperforming wheat in terms of biomass yield and forage quality, particularly in less favorable environments. This study highlights that triticale generally exhibits higher grain yield stability and better adaptability to water-limited and nitrogen-limited conditions compared to wheat. Additionally, triticale's nutritional profile, including crude protein content and total digestible nutrients, is comparable to that of wheat, making it a viable alternative for both grain and forage production. This study also discusses the potential of triticale in improving soil health and reducing nutrient leaching when used as a cover crop. Overall, this study underscores the potential benefits of incorporating triticale into agricultural systems, particularly in regions facing abiotic stressors such as drought and poor soil fertility.
Keywords Triticale; Wheat, Yield stability; Nutritional content; Abiotic stress adaptability

1 Introduction

Wheat (*Triticum* spp.) is one of the most significant cereal crops globally, playing a crucial role in human nutrition and food security. Its success is largely attributed to its versatile grain proteins, particularly gluten, which allows for the production of a wide variety of foods (Sousa et al., 2021). Wheat is cultivated in diverse climatic zones and has been a staple food for thousands of years, evolving from ancient varieties like einkorn, emmer, and spelt to the modern hexaploid and tetraploid varieties that dominate global production today (Sousa et al., 2021). On the other hand, triticale (×*Triticosecale Wittmack*) is a relatively recent man-made hybrid developed by crossing wheat and rye (*Secale cereale* L.). This hybridization aims to combine the favorable traits of both progenitor species, resulting in a crop that is more adaptable to less favorable environments and capable of producing higher biomass yield and forage quality (Ayalew et al., 2018).

Comparative studies between triticale and wheat are essential for several reasons. Firstly, they provide insights into the adaptability of these crops to various environmental conditions, which is crucial for improving food security in the face of climate change (Wan et al., 2022; Filip et al., 2023). Secondly, understanding the differences in yield and nutritional content between triticale and wheat can guide breeding programs aimed at enhancing crop quality and resilience (Ayalew et al., 2018). Such studies also help in identifying the specific conditions under which each crop performs best, thereby optimizing agricultural practices and resource use (Wan et al., 2022). Moreover, triticale's potential as a cover crop to improve soil health and reduce nutrient leaching further underscores the need for comprehensive comparative analyses (Ayalew et al., 2018).

This study conducts a comparative analysis of triticale and wheat in terms of yield, adaptability, and nutritional content. By synthesizing existing research, this study highlights the strengths and weaknesses of each crop, providing a holistic understanding that can inform future agricultural practices and breeding programs; examines how environmental factors affect the yield and quality of these crops, assess their nutritional profiles, and explores their potential uses in various agricultural systems. Through this comparative analysis, this study seeks to contribute to the development of more resilient and productive cereal crops, ultimately enhancing global food security.

2 Agronomic Characteristics

2.1 Yield potential

2.1.1 Comparative yield performance

Triticale generally exhibits a higher grain yield (GY) compared to bread wheat (*Triticum aestivum* L.), particularly in Mediterranean environments where water deficits are common during spring and summer. Studies have shown that triticale has a higher number of kernels per spike and greater 1000 kernel weight, despite having fewer spikes per square meter compared to wheat. This results in a higher overall yield for triticale (Figure 1) (Méndez-Espinoza et al., 2019). Additionally, triticale's yield stability across various environments has been demonstrated to be superior to that of wheat, with triticale lines showing good adaptability and stable yields in diverse conditions (Farokhzadeh et al., 2022).

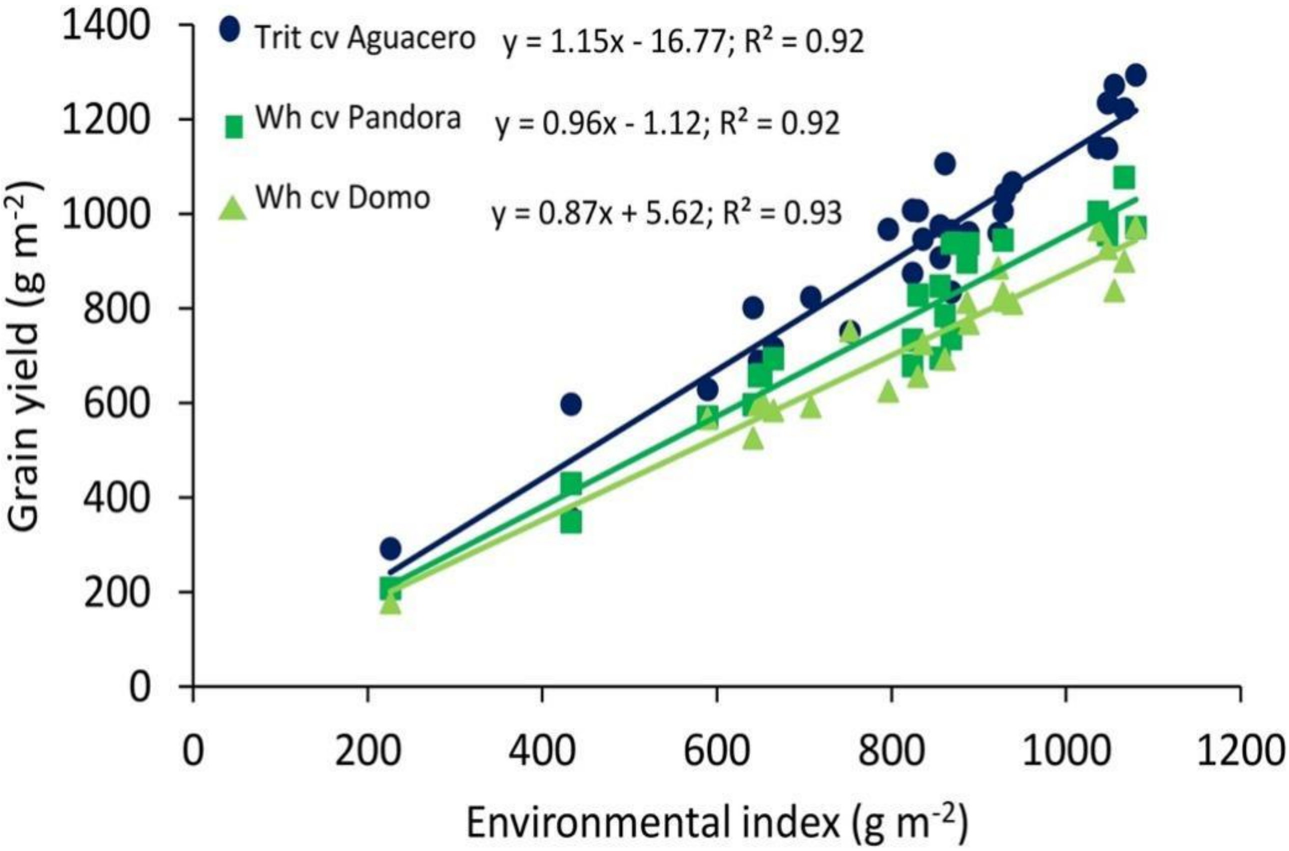

Figure 1 Relationships between the environmental index and grain yield of spring wheat (cv. Pandora-INIA) and triticale (cv. Aguacero-INIA) (Adopted from Méndez-Espinoza et al., 2019)

Image caption: Data are from 10 localities in 2004 and 2005 (eight Mediterranean and two temperate areas), and two localities (Cauquenes and Santa Rosa), under well-watered and water-deficit conditions, in 2014, 2015, and 2016. Also, data comparing triticale cv. Aguacero-INIA and the spring wheat cv. Domo at nine localities in 2001 and 2002 were included in the analysis. The comparison of the regression lines indicated significant difference among the slopes ($P < 0.01$) and intercepts ($P < 0.0001$) (Adopted from Méndez-Espinoza et al., 2019)

Méndez-Espinoza et al. (2019) illustrates the relationship between grain yield and environmental index for triticale (cv. Aguacero-INIA) and spring wheat (cv. Pandora-INIA and Domo) across various locations and conditions. The regression analysis shows that triticale has a higher regression coefficient (Finlay and Wilkinson slope), indicating a more stable yield across diverse environmental conditions compared to wheat. This stability is coupled with generally higher yields, even in extreme environments. The significant differences in slopes ($P < 0.01$) and intercepts ($P < 0.0001$) between the crops underscore triticale's superior adaptability and yield stability. Triticale also outperforms wheat in grain yield due to its larger grain size, which is consistent across varying grain numbers per square meter. This highlights triticale's potential as a robust crop in diverse and challenging environments.

2.1.2 Factors affecting yield

Several factors influence the yield of both triticale and wheat. Drought significantly reduces the yield of wheat, with continuous drought stress causing a more substantial yield reduction compared to terminal drought stress (Wan et al., 2022). Soil organic matter (SOM) also plays a crucial role in yield potential, with higher concentrations of soil organic carbon (SOC) being associated with increased yields, although the benefits level off at around 2% SOC (Oldfield et al., 2018). Furthermore, the initial soil nutrient status, particularly phosphorus (P) and potassium (K), significantly affects wheat yield, with better soil health leading to higher productivity (Li et al., 2022).

2.2 Adaptability to different environments

2.2.1 Climate resilience

Triticale has shown a more stable response to varying environmental conditions compared to wheat, making it more resilient to climate fluctuations. This stability is attributed to triticale's higher photosynthetic rates and better water-use efficiency, which contribute to its higher yield under different environmental conditions (Méndez-Espinoza et al., 2019). In contrast, wheat's yield and protein content are more adversely affected by drought, with significant reductions in grain yield and protein yield under drought conditions (Wan et al., 2022).

2.2.2 Soil requirements

Both triticale and wheat benefit from soils with high organic matter content. Higher SOC levels are associated with increased yields for both crops, although the relationship is more pronounced in wheat. Maintaining and building SOM is essential for sustainable intensification and improving yield potential (Oldfield et al., 2018). Additionally, soil nutrient status, particularly the availability of P and K, is critical for optimizing yield. Integrated nutrient management approaches, including the use of phosphate-solubilizing bacteria (PSB), have been shown to enhance P uptake and yield effectiveness in wheat under various agro-climatic conditions (Yahya et al., 2023).

2.2.3 Water use efficiency

Triticale exhibits higher water-use efficiency compared to wheat, which is a significant advantage in water-limited environments. This efficiency is linked to triticale's higher chlorophyll content, leaf net photosynthesis, and maximum rate of electron transport, which collectively contribute to its superior yield performance under both well-watered and water-limited conditions (Méndez-Espinoza et al., 2019). In wheat, optimizing water and nitrogen management practices can significantly improve water productivity and nitrogen use efficiency, thereby enhancing yield and sustainability (Li et al., 2022).

In summary, triticale generally outperforms wheat in terms of yield potential and adaptability to different environments, particularly under water-limited conditions. Factors such as soil organic matter, nutrient status, and water-use efficiency play crucial roles in determining the yield and resilience of both crops.

3 Nutritional Content

3.1 Protein composition

Triticale and wheat both serve as significant sources of protein, but they differ in their specific protein compositions. Wheat is rich in gluten proteins, which are crucial for bread-making quality. These proteins are divided into gliadins and glutenins, which have been extensively studied for their roles in determining the elasticity and extensibility of dough (Khalid et al., 2023). Triticale, on the other hand, has a varied amino acid profile, which makes it a valuable feed grain. Studies have shown that sprouted triticale grains contain a high percentage of crude protein, with some varieties reaching up to 15.83% (Kassymbek, 2023). This makes triticale a good alternative for animal feed, providing essential amino acids and enhancing the digestibility of the feed (Kassymbek, 2023).

3.2 Carbohydrates and fiber

Both triticale and wheat are rich in carbohydrates, which are the primary source of energy in human and animal diets. Wheat grains contain approximately 72.29% carbohydrates, making them a significant energy source (Mustapha et al, 2019). Triticale also has a high carbohydrate content, with a notable presence of starch and non-starch polysaccharides, which contribute to its versatility in food production (Zhu, 2018). In terms of dietary fiber, wheat is known for its high dietary fiber content, particularly in the bran, which includes both insoluble and soluble fibers (Köse et al., 2023). Triticale also contains dietary fiber, but the specific fiber fractions can vary significantly among different varieties (Biel et al., 2020).

3.3 Vitamins and minerals

Wheat is a rich source of essential vitamins and minerals, including B-group vitamins, vitamin E, and minerals such as iron (Fe), zinc (Zn), magnesium (Mg), and phosphorus (P) (Shariatipour et al., 2021; Khalid et al., 2023). Triticale, while primarily used as animal feed, also contains significant amounts of vitamins and minerals. For instance, sprouted triticale grains have been found to contain high levels of potassium (K) and phosphorus (P), which are essential for both human and animal health (Kassymbek, 2023). Additionally, biofortification efforts have shown that foliar zinc application can significantly increase the zinc content in triticale grains, making it a potential candidate for addressing zinc deficiency in human diets (Dhaliwal et al., 2019).

3.4 Implications for human and animal consumption

The nutritional profiles of triticale and wheat have important implications for their use in human and animal diets. Wheat, with its high protein content and essential vitamins and minerals, is a staple food crop that supports human nutrition worldwide (Ciudad-Mulero et al., 2020; Khalid et al., 2023). The presence of gluten proteins makes it particularly valuable for bread-making and other food products. Triticale, with its high protein and carbohydrate content, is primarily used as animal feed, but its nutritional composition also makes it suitable for human consumption in various forms, such as bakery products and pasta (Zhu, 2018). The high fiber content in both grains contributes to better digestive health, while the presence of essential minerals supports overall health and well-being (Dhaliwal et al., 2019; Mustapha et al, 2019; Biel et al., 2020). The potential for biofortification in both crops further enhances their nutritional value, making them important components of strategies to combat malnutrition (Dhaliwal et al., 2019; Shaukat et al., 2021).

4 Case Study

4.1 Description of the study area

The study area encompasses diverse agricultural environments, including regions with varying levels of water and nitrogen availability, as well as areas affected by salinity and other abiotic stresses. The primary focus is on regions in California, the Southern Great Plains of the United States, and Mediterranean climates, where both triticale and wheat are cultivated under different environmental conditions (Méndez-Espinoza et al., 2019; Shaukat et al., 2021; Tamagno et al., 2022; Upreti et al., 2022).

4.2 Comparative performance of triticale and wheat in the region

Triticale has demonstrated superior performance compared to wheat in several key areas. In California, triticale outyielded wheat by 11% under average conditions and by 19% under nitrogen-limited conditions, although wheat was 3% more productive in water-limited environments (Figure 2) (Tamagno et al., 2022). In the Southern Great Plains, triticale showed better biomass yield and forage quality, making it a viable alternative for both grain and forage production (Upreti et al., 2022). In Mediterranean environments, triticale exhibited higher grain yield and yield stability compared to wheat, particularly under water-limited conditions (Méndez-Espinoza et al., 2019).

Tamagno et al. (2022) presents a comparison of grain yield, protein yield, and protein concentration between wheat and triticale under average, water-stressed, and nitrogen-stressed conditions. Triticale outperforms wheat in grain yield under average and nitrogen-stressed environments, with significant differences of 606 kg/ha and 795 kg/ha, respectively. However, wheat shows higher yields under water-stressed conditions. Despite triticale's lower protein concentration across all conditions, its higher grain yield reduces the gap in protein yield, even surpassing wheat under nitrogen stress. This indicates that while triticale may have lower protein content, its robust performance in yield, especially under nitrogen stress, makes it a strong candidate for challenging growing conditions, balancing overall productivity with nutritional output.

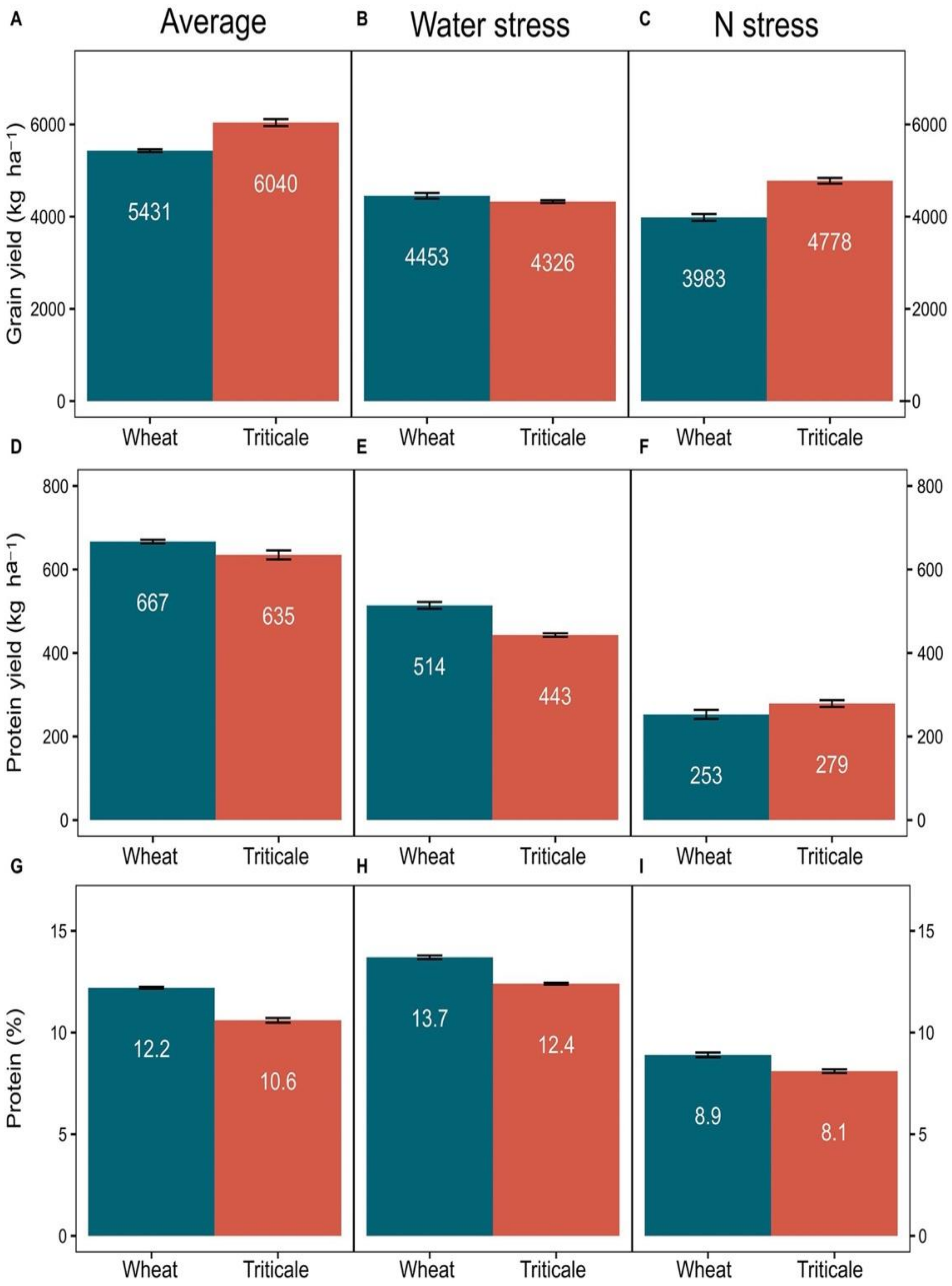

Figure 2 Estimated marginal means (± SE) for grain yield (A–C), protein yield (D–F), and protein concentration (G–I) for common wheat and triticale growing under average conditions, water and N stressed environments. Numbers in white are the values for each bar (Adopted from Tamagno et al., 2022)

4.3 Analysis of local adaptability and yield

Triticale's adaptability to various environmental stresses, such as salinity and water deficit, has been well-documented. In salinity-affected regions, triticale lines demonstrated higher yield stability and adaptability compared to wheat (Farokhzadeh et al., 2022). Additionally, triticale's higher photosynthetic rates and better water-use efficiency contributed to its superior performance in Mediterranean climates (Méndez-Espinoza et al., 2019). The crop's ability to produce more grain per unit of water and nitrogen inputs further underscores its adaptability and potential for sustainable agriculture (Tamagno et al., 2022).

4.4 Nutritional impact on the local population

The nutritional content of triticale and wheat has significant implications for local populations. Triticale has been shown to produce more nutritious baked products when blended with wheat, potentially reducing the environmental footprint of food production (Tamagno et al., 2022). Moreover, foliar zinc application has been effective in biofortifying both triticale and wheat, enhancing their zinc content and addressing micronutrient deficiencies in human diets (Dhaliwal et al., 2019). The higher protein content in certain triticale varieties also contributes to improved nutritional outcomes (Upreti et al., 2022).

In summary, triticale's superior yield, adaptability to various environmental stresses, and enhanced nutritional content make it a promising alternative to wheat in diverse agricultural regions. These findings highlight the potential benefits of incorporating triticale into local farming systems to improve both agricultural sustainability and nutritional security.

5 Economic Considerations

5.1 Market demand and pricing

The market demand and pricing for triticale and wheat significantly influence their economic viability. Triticale, despite its higher yield in certain conditions, often faces lower market prices compared to wheat. For instance, a study conducted in Washington revealed that the market price for triticale grain was consistently lower than that for wheat, making it less economically competitive despite its higher grain yield (Schillinger and Archer, 2020). This price disparity is a critical factor that affects the overall profitability of triticale cultivation.

5.2 Cost of cultivation and profit margins

The cost of cultivation and profit margins for triticale and wheat vary based on several factors, including input costs and yield. In a long-term study in a dry Mediterranean climate, it was found that winter triticale produced more grain than winter wheat but was not economically competitive due to its lower market price. The study suggested that a 15-21% increase in triticale price or grain yield would be necessary for it to match the profitability of wheat rotations (Schillinger and Archer, 2020). Another study highlighted that the economic efficiency of triticale production could be enhanced by optimizing nitrogen fertilization and tillage methods. The gross margin was higher for hybrid triticale forms under traditional tillage with higher nitrogen rates, indicating that careful management practices can improve profitability (Derejko et al., 2020).

5.3 Economic viability in different regions

The economic viability of triticale and wheat varies across different regions due to climatic and soil conditions. In the Amur region, triticale showed competitive yields compared to traditional spring crops, with higher productivity in the southern zone but lower in the central and northern zones (Muratov et al., 2023). In Mediterranean environments, triticale exhibited higher yield stability and productivity compared to wheat, particularly under water-limited conditions, suggesting its potential economic advantage in such regions (Méndez-Espinoza et al., 2019). Additionally, in the semiarid region of Minas Gerais, triticale demonstrated higher dry matter yield and better nutritional quality for forage compared to wheat, indicating its suitability and economic potential for forage production in such environments (Vieira et al., 2022).

Overall, while triticale shows promise in terms of yield and adaptability, its economic viability is heavily influenced by market prices, cost of cultivation, and regional suitability. Strategic management practices and market adjustments are essential to enhance its profitability and competitiveness with wheat.

6 Environmental Impact

6.1 Soil health and fertility

Triticale and wheat have different impacts on soil health and fertility, primarily due to their varying nutrient requirements and residue management. Triticale has been shown to have higher nitrogen use efficiency compared to wheat, particularly under nitrogen-limited conditions, which can lead to reduced nitrogen fertilizer requirements and potentially lower soil nitrogen depletion (Tamagno et al., 2022). Additionally, dual-purpose cover crops, including triticale, can capture significant amounts of nitrogen and phosphorus from the soil, which helps in nutrient management and reduces the risk of nutrient leaching (Glaze-Corcoran et al., 2023). The use of triticale in integrated cropping systems has also been associated with improved soil organic carbon content, which is crucial for maintaining soil health and fertility (Jańczak-Pieniążek, 2023).

6.2 Biodiversity considerations

The cultivation of triticale and wheat can influence biodiversity in agricultural systems. Triticale, being a hybrid crop, often exhibits greater resilience to abiotic stresses, which can lead to more stable yields and potentially less need for chemical inputs such as pesticides and fertilizers (Tamagno et al., 2022). This reduced reliance on chemical inputs can benefit local biodiversity by minimizing the negative impacts on non-target organisms and soil microbial communities. Furthermore, the use of triticale as a cover crop can enhance biodiversity by providing habitat and food resources for various organisms, thereby supporting ecosystem services such as pollination and pest control (Glaze-Corcoran et al., 2023). In contrast, conventional wheat cultivation often involves higher chemical inputs, which can negatively impact biodiversity (Jańczak-Pieniążek, 2023).

6.3 Carbon footprint and sustainability

The carbon footprint and sustainability of triticale and wheat production are influenced by their respective resource use efficiencies and management practices. Triticale has been shown to produce more grain per unit of water and nitrogen fertilizer inputs compared to wheat, particularly in high-yielding environments (Tamagno et al., 2022). This higher resource use efficiency can translate to lower greenhouse gas emissions associated with fertilizer production and application. Additionally, the integration of triticale into cropping systems can contribute to carbon sequestration through increased soil organic carbon content (Oldfield et al., 2018). Life cycle assessments have demonstrated that optimizing water and nitrogen management in wheat production can also reduce greenhouse gas emissions, highlighting the importance of sustainable practices in both crops (Li et al., 2022). Overall, the adoption of triticale in appropriate environments and management systems can enhance the sustainability of agricultural production by reducing the carbon footprint and improving resource use efficiency.

By considering these environmental impacts, the comparative analysis of triticale and wheat highlights the potential benefits of triticale in terms of soil health, biodiversity, and sustainability, while also recognizing the importance of tailored management practices to maximize these benefits.

7 Future Prospects and Challenges

7.1 Breeding and genetic improvement

The future of triticale and wheat breeding lies in leveraging advanced genetic tools and techniques to enhance yield, adaptability, and nutritional content. Triticale, a hybrid of wheat and rye, has shown potential for both grain and forage production, but its genetic improvement has lagged behind other small grains. Advances in molecular biology and genomic resources from both wheat and rye can be exploited to improve triticale. Techniques such as gene mapping and genomic selection can increase selection precision and reduce time and cost in breeding programs (Ayalew et al., 2018). Similarly, wheat improvement can benefit from state-of-the-art genome-editing technologies. Molecular tools such as CRISPR/Cas9 have enabled the precise modification of genes associated with yield and quality traits, leading to the development of high-yielding and nutritionally superior crop varieties (Xu and Su, 2024). These technologies, combined with other molecular breeding strategies like GWAS and high-throughput genotyping, can facilitate the development of elite wheat cultivars that are resilient to climate change and other environmental stresses (Li et al., 2021).

7.2 Technological innovations in cultivation

Technological innovations in cultivation practices are essential to maximize the yield and adaptability of both triticale and wheat. For triticale, the use of synthetic fertilizers in combination with organic amendments like press mud and animal manure has been shown to significantly improve growth and yield under various irrigation regimes (Sher et al., 2022). Additionally, the development of cultivars with deeper and longer roots can enhance water use efficiency and yield, particularly in environments where water is available deeper in the soil profile. However, selecting for these root traits remains challenging and depends heavily on environmental conditions (Severini et al., 2020). For wheat, the integration of high-resolution genome-wide association studies (GWAS) can identify genomic regions and candidate genes for important agronomic traits, thereby aiding in the development of high-yield, stress-tolerant varieties (Pang et al., 2020).

7.3 Policy and regulatory aspects

Policy and regulatory frameworks play a crucial role in the adoption and success of new crop varieties. For triticale, there is a growing interest in its use as an alternative to wheat for livestock feed and as an industrial energy crop. However, fungal diseases like leaf and stripe rusts are significant limiting factors. The incorporation of slow-rusting genes from wheat into triticale through cross-hybridizations and marker-assisted selection can enhance its disease resistance and overall viability (Skowrońska et al., 2020). For wheat, policies that support the use of genome-editing technologies and other advanced breeding methods are essential to address the challenges posed by climate change, population growth, and environmental degradation. Regulatory frameworks should also promote sustainable agricultural practices that minimize environmental pollution while ensuring food security (Li et al., 2021).

In conclusion, the future prospects for triticale and wheat involve a combination of advanced genetic tools, innovative cultivation practices, and supportive policy frameworks. These efforts will be crucial in meeting the global demand for food and feed while addressing the challenges posed by environmental and climatic changes.

8 Concluding Remarks

The comparative analysis of triticale and wheat has revealed several key insights into their yield, adaptability, and nutritional content. Triticale, a hybrid of wheat and rye, generally exhibits superior adaptability to less favorable environments and higher yield stability compared to wheat. Studies have shown that triticale outperforms wheat in terms of biomass yield and forage quality, making it a promising crop for both grain and forage production. Additionally, triticale demonstrates better performance under nitrogen-limited conditions and has a higher efficiency of water and nitrogen use, which contributes to its sustainability in diverse production environments. Nutritionally, triticale offers comparable or superior protein content and digestibility, making it a valuable crop for both human consumption and animal feed.

Farmers should consider incorporating triticale into their crop rotations, especially in regions with challenging growing conditions such as salinity, drought, or nutrient-poor soils. Triticale's superior adaptability and yield stability can enhance overall farm productivity and sustainability. Policymakers should support research and development efforts aimed at improving triticale varieties, particularly in the areas of genetic mapping and molecular breeding, to further enhance its agronomic traits and nutritional value. Additionally, promoting the use of triticale as a cover crop can improve soil health and reduce nutrient leaching, contributing to more sustainable agricultural practices.

Future research should focus on several key areas to fully realize the potential of triticale. First, there is a need for more comprehensive studies comparing the long-term environmental impacts and economic benefits of triticale versus wheat in various agro-ecological zones. Second, advancements in molecular biology and genomic selection should be leveraged to develop triticale varieties with enhanced stress tolerance, higher nutritional quality, and better grain yield. Third, further investigation into the optimal management practices for triticale, including irrigation, fertilization, and pest control, will help maximize its productivity and sustainability. Finally, exploring the potential of triticale in new markets, such as bioenergy and functional foods, could open up additional avenues for its utilization and commercialization.

Acknowledgments
CropSci Publisher sincerely thanks the reviewers for their valuable comments and suggestions.

Conflict of Interest Disclosure
Authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References
Ayalew H., Kumssa T., Butler T., and Ma X., 2018, Triticale improvement for forage and cover crop uses in the southern great plains of the United States, Frontiers in Plant Science, 9: 1130.
https://doi.org/10.3389/fpls.2018.01130
PMid:30127797 PMCid:PMC6087761

Biel W., Kazimierska K., and Bashutska U., 2020, Nutritional value of wheat, triticale, barley and oat grains, Zootechnica, 19(2): 19-28.
https://doi.org/10.21005/asp.2020.19.2.03

Ciudad-Mulero M., Barros L., Fernandes Â., Ferreira I., Callejo M., Matallana-González M., Fernández-Ruíz V., Morales P., and Carrillo J., 2020, Potential health claims of durum and bread wheat flours as functional ingredients, Nutrients, 12(2): 504.
https://doi.org/10.3390/nu12020504
PMid:32079210 PMCid:PMC7071334

Derejko A., Studnicki M., Wójcik-Gront E., and Gacek E., 2020, Adaptive grain yield patterns of triticale (×*Triticosecale Wittmack*) cultivars in six regions of Poland, Agronomy, 10(3): 415.
https://doi.org/10.3390/agronomy10030415

Dhaliwal S., Ram H., Shukla A., and Mavi G., 2019, Zinc biofortification of bread wheat, triticale, and durum wheat cultivars by foliar zinc fertilization, Journal of Plant Nutrition, 42(8): 813-822.
https://doi.org/10.1080/01904167.2019.1584218

Farokhzadeh S., Hassani H., Mohammadi-Nejad G., and Zinati Z., 2022, Evaluation of grain yield stability of tritipyrum as a novel cereal in comparison with triticale lines and bread wheat varieties through univariate and multivariate parametric methods, PLoS ONE, 17(9): e0274588.
https://doi.org/10.1371/journal.pone.0274588
PMid:36174006 PMCid:PMC9703957

Filip E., Woronko K., Stępień E., and Czarniecka N., 2023, An overview of factors affecting the functional quality of common wheat (*Triticum aestivum* L.), International Journal of Molecular Sciences, 24(8): 7524.
https://doi.org/10.3390/ijms24087524
PMid:37108683 PMCid:PMC10142556

Glaze-Corcoran S., Smychcovich A., and Hashemi M., 2023, Dual-purpose rye, wheat, and triticale cover crops offer increased forage production and nutrient management but demonstrate nitrogen immobilization dynamics, Agronomy, 13(6): 1517.
https://doi.org/10.3390/agronomy13061517

Jańczak-Pieniążek M., 2023, The influence of cropping systems on photosynthesis, yield, and grain quality of selected winter triticale cultivars, Sustainability, 15(14): 11075.
https://doi.org/10.3390/su151411075

Kassymbek R., 2023, The feed value and amino acid composition of sprouted triticale grains, The Journal of Almaty Technological University, pp.115-123.
https://doi.org/10.48184/2304-568X-2023-2-115-123

Khalid A., Hameed A., and Tahir M., 2023, Wheat quality: a review on chemical composition, nutritional attributes, grain anatomy, types, classification, and function of seed storage proteins in bread making quality, Frontiers in Nutrition, 10: 1053196.
https://doi.org/10.3389/fnut.2023.1053196
PMid:36908903 PMCid:PMC9998918

Köse Ö., Mut Z., Kardeş Y., and Akay H., 2023, Grain-bran quality parameters and agronomic traits of bread wheat cultivars, Turkish Journal Of Field Crops, 28(2): 269-278.
https://doi.org/10.17557/tjfc.1336316

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
PMid:34327324 PMCid:PMC8299080

Li Z., Cui S., Zhang Q., Xu G., Feng Q., Chen C., and Li Y., 2022, Optimizing wheat yield, water, and nitrogen use efficiency with water and nitrogen inputs in China: a synthesis and life cycle assessment, Frontiers in Plant Science, 13: 930484.
https://doi.org/10.3389/fpls.2022.930484
PMid:35783937 PMCid:PMC9244784

Méndez-Espinoza A., Romero-Bravo S., Estrada F., Garriga M., Lobos G., Castillo D., Matus I., Aranjuelo Í., and Pozo A., 2019, Exploring agronomic and physiological traits associated with the differences in productivity between triticale and bread wheat in mediterranean environments, Frontiers in Plant Science, 10: 404.
https://doi.org/10.3389/fpls.2019.00404
PMid:31024582 PMCid:PMC6460938

Muratov A., Epifantsev V., and Tikhonchuk P., 2023, Competitiveness of triticale among spring crops of the Amur region, E3S Web of Conferences. EDP Sciences, 371: 01082.
https://doi.org/10.1051/e3sconf/202337101082

Mustapha K., Zubairu H., and Adamu A., 2019, Comparison of nutritional values of wheat (*Triticum aestivum*) and acha (*Digitaria exilis*) grains, Bayero Journal of Pure and Applied Sciences, 11(1): 133-138.
https://doi.org/10.4314/bajopas.v11i1.22S

Oldfield E., Bradford M., and Wood S., 2018, Global meta-analysis of the relationship between soil organic matter and crop yields, Soil, 5(1): 15-32.
https://doi.org/10.5194/soil-5-15-2019

Pang Y., Liu C., Wang D., Amand P., Bernardo A., Li W., He F., Li L., Wang L., Yuan X., Dong L., Su Y., Zhang H., Zhao M., Liang Y., Jia H., Shen X., Lu Y., Jiang H., Wu Y., Li A., Wang H., Kong L., Bai G., and Liu S., 2020, High-resolution genome-wide association study identifies genomic regions and candidate genes for important agronomic traits in wheat, Molecular plant, 13(9): 1311-1327.
https://doi.org/10.1016/j.molp.2020.07.008
PMid:32702458

Schillinger W., and Archer D., 2020, Winter triticale: a long-term cropping systems experiment in a dry Mediterranean climate, Agronomy, 10(11): 1777.
https://doi.org/10.3390/agronomy10111777

Severini A., Wasson A., Evans J., Richards R., and Watt M., 2020, Root phenotypes at maturity in diverse wheat and triticale genotypes grown in three field experiments: Relationships to shoot selection, biomass, grain yield, flowering time, and environment, Field Crops Research, 255: 107870.
https://doi.org/10.1016/j.fcr.2020.107870

Shariatipour N., Heidari B., Tahmasebi A., and Richards C., 2021, Comparative genomic analysis of quantitative trait loci associated with micronutrient contents, grain quality, and agronomic traits in wheat (*Triticum aestivum* L.), Frontiers in Plant Science, 12: 709817.
https://doi.org/10.3389/fpls.2021.709817
PMid:34712248 PMCid:PMC8546302

Shaukat M., Sun M., Ali M., Mahmood T., Naseer S., Maqbool S., Rehman S., Mahmood Z., Hao Y., Xia X., Rasheed A., and He Z., 2021, Genetic gain for grain micronutrients and their association with phenology in historical wheat cultivars released between 1911 and 2016 in Pakistan, Agronomy, 11(6): 1247.
https://doi.org/10.3390/agronomy11061247

Sher A., Nawaz M., Hasnain Z., Mehmood K., Chattha M., Ijaz M., Sattar A., Ibrar D., Bashir S., Khan M., Gul S., Irshad S., Fahad S., Ahmed N., Habibullah, Rais A., and Khan S., 2022, Impact of press mud and animal manure in comparison with NPK on the growth and yield of triticale (*Triticosecale wittmack*) genotypes cultivated under various irrigation regimes, Agronomy, 12(12): 2944.
https://doi.org/10.3390/agronomy12122944

Skowrońska R., Mariańska M., Ulaszewski W., Tomkowiak A., Nawracała J., and Kwiatek M., 2020, Development of triticale×wheat prebreeding germplasm with loci for slow-rusting resistance, Frontiers in Plant Science, 11: 447.
https://doi.org/10.3389/fpls.2020.00447
PMid:32457768 PMCid:PMC7221182

Sousa T., Ribeiro M., Sabença C., and Igrejas G., 2021, The 10,000-year success story of wheat! Foods, 10(9): 2124.
https://doi.org/10.3390/foods10092124
PMid:34574233 PMCid:PMC8467621

Tamagno S., Pittelkow C., Fohner G., Nelsen T., Hegarty J., Carter C., Vang T., and Lundy M., 2022, Optimizing water and nitrogen productivity of wheat and triticale across diverse production environments to improve the sustainability of baked products, Frontiers in Plant Science, 13: 952303.
https://doi.org/10.3389/fpls.2022.952303
PMid:36161023 PMCid:PMC9491324

Upreti S., Ghimire R., Singh N., Bhandari G., and Banskota N., 2022, Production performance and nutrient composition of fodder triticale (x *Triticosecale* W.), Journal of Nepal Agricultural Research Council, 8: 101-114.
https://doi.org/10.3126/jnarc.v8i.44871

Vieira E., Albuquerque C., Rigueira J., Gomes V., Coelho M., Júnior V., Monção F., Santana I., Hora F., and Gomes M., 2022, Production and nutritional value of wheat and triticale cultivars in different harvest times in the Minas Gerais semiarid, Semina Ciências Agrárias, 43(1): 381-396.
https://doi.org/10.5433/1679-0359.2022v43n1p381

Wan C., Dang P., Gao L., Wang J., Tao J., Qin X., Feng B., and Gao J., 2022, How does the environment affect wheat yield and protein content response to drought? a meta-analysis, Frontiers in Plant Science, 13: 896985.
https://doi.org/10.3389/fpls.2022.896985
PMid:35845696 PMCid:PMC9280411

Xu R.G., and Su Q.X., 2024, Molecular tools and genomic resources in triticeae: enhancing crop productivity, Triticeae Genomics and Genetics, 15(2): 66-76.

Yahya M., Rasul M., Hussain S., Dilawar A., Ullah M., Rajput L., Afzal A., Asif M., Wubet T., and Yasmin S., 2023, Integrated analysis of potential microbial consortia, soil nutritional status, and agro-climatic datasets to modulate P nutrient uptake and yield effectiveness of wheat under climate change resilience, Frontiers in Plant Science, 13: 1074383.
https://doi.org/10.3389/fpls.2022.1074383
PMid:36714699 PMCid:PMC9878846

Zhu F., 2018, Triticale: nutritional composition and food uses, Food Chemistry, 241: 468-479.
https://doi.org/10.1016/j.foodchem.2017.09.009
PMid:28958555