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# The nutritional value of triticale and its potential to replace wheat for sustainability. Article Review

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**ABSTRACT**
Recently, agricultural productivity and food security have been seriously threatened by climate changes, which has increased poverty globally. So, it is necessary to address these changes and minimize their detrimental impacts by sowing crops like triticale that are resistant to unfavorable environmental conditions and have consistency in productivity. Triticale's high nutritional value, high productivity and ability to grow on marginal areas as well as capability to adapt to tough environments make it fundamental for treating food deficiency and achieving global food security. This makes it a promising crop and a viable alternative to wheat when environmental conditions are unfavorable. Triticale combines the key characteristics of its parent crops, wheat and rye, with high seed protein content, high-quality essential amino acid content, and high biological value, allowing it to be used not only as a raw material in food products but also in animal feed. In addition to being less affected by environmental stresses and resistant to various diseases. An increase in grain yield and quality and encourages the expansion of its food uses as a result of the increasing demand for these products by consumers. Despite its advantages, its cultivation in Iraq is limited and at an experimental level, which requires attention to this crop to provide a supporting source for wheat.

**KEYWORDS:** nutritional value of triticale, wheat replacement with triticale, environmental impact.

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# القيمة الغذائية وامكانية استبدال الحنطة بالتريتيكيلي لتحقيق الاستدامة: مقالة مراجعة

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**الملخص**
التغيرات المناخية في السنوات الأخيرة اصبحت تشكل تهديدًا حقيقيًا للإنتاج الزراعي والأمن الغذائي وزيادة نسبة الفقر في مستوى العالم, ولذا فإن هناك حاجة لمواجهة هذه التغيرات والحد من تأثيرها السلبي عن طريق زراعة المحاصيل التي تمتاز باستقرار إنتاجيتها ومقاومتها للظروف البيئية غير الملائمة ومنها التريتيكيلي لتحقيق الأمن الغذائي العالمي وسد النقص الحاصل في الغذاء نتيجة لمقدرة هذا المحصول في التكيف مع البيئات القاسية وإنتاجيته المرتفعة فضلا عن مقدرته في النمو في الأراضي الهامشية الأمر الذي يجعله محصولًا واعدًا وساندا للحنطة عند عدم ملائمة الظروف البيئية. التريتيكيلي محصول يجمع بين أهم الصفات الرئيسة لأبائه الحنطة والشيلم، إذ يتميز بمحتوى الحبوب المرتفع من البروتين ومحتواه العالي الجودة من الأحماض الأمينية الاساسية والجودة البيولوجية مما يسمح باستخدامه كمادة خام ليس فقط في المنتجات الغذائية بل في صناعة الأعلاف أيضًا. فضلا عن كونه أقل تأثرًا بالإجهادات البيئية ومقاومته لمختلف الأمراض مما يسمح بزيادة حاصل الحبوب وجودتها ويشجع في توسيع نطاق استعمالاته الغذائية نتيجة للطلب المتزايد على هذه المنتجات من قبل المستهلكين، وعلى الرغم من مميزاته إلا أن زراعته بالعراق محدودة وعلى مستوى تجريبي الأمر الذي يتطلب الاهتمام بهذا المحصول لتوفير مصدر داعم لمحصول الحنطة.
**الكلمات المفتاحية:** القيمة الغذائية للتريتيكيلي, استبدال الحنطة بالتريتيكيلي, التأثير البيئي.

## INTRODUCTION

Triticale (*Triticosecale* x *Wittmack*) is an evolutionarily recent crop. The first varieties were introduced into production a little over 30 years ago, Currently, its cultivation area worldwide exceeds 3 million hectares. The largest areas of triticale cultivation are located in Poland (840,000 hectares), Germany (537,000 hectares), China (550,000 hectares), Australia (400,000 hectares), Ukraine (130,000 hectares) and Russia the cultivated area ranges between 220,000 and 250,000 hectares (Tutel'yan and Popova, 2002; Grabovec, 2004). Agricultural producers are steadily increasing their attention in this crop and its cultivation areas are extending. It's potential to have a higher percentage

of protein, better digestibility, high yield, tolerance to unsuitable soil and climate conditions, and resistance to diseases when compared to wheat explain this special interest (De Zutter et al., 2023; Gaviley et al., 2024). Triticale has been usage as green and grain fodder for many years, Recently, breeders have worked to develop and introduce appropriate grain varieties for flour production to making bread and confectionery products (Ghendov-Mosanu et al., 2024). Triticale is widely produced in many countries of the world because it offers many agricultural advantages, such as high yield potential, disease resistance, environmental tolerance, and high-quality grains that are a rich source of protein and biologically active components. Although the quantities of soluble and insoluble fiber vary, its dietary fiber contain is comparable to that of wheat grains. Despite this, its usage in baking is restricted because of the α-amylase enzyme's activity and the dough's poor rheological qualities, which make it a non-bread grain crop (Fraś et al., 2016).

Triticale is a cereal crop bred by hybridizing wheat and rye, Its attention as a valuable crop increased due to its ability to combine the desirable traits of its parent plants, Despite the well-known successes in wheat breeding programs and the development of new varieties that combine high productivity, good nutritional characteristics, lodging resistance, fertilization response, and other characteristics, these varieties lack some important qualities, most notably weak resistance to certain soil, climatic, and unfavorable environmental conditions compared to rye (Filip et al., 2023).

In contrast to wheat, rye is more resilient to low temperatures, high salinity and high soil acidity, Furthermore, it requires less organic and in-organic fertilizers and is less prone to fungal infections, Morphologically speaking, rye can produce 50–60 spikelets per spike, while wheat usually produces about 20–25. This suggests that rye has the probable to produce more grain (Celestina et al., 2023). Triticale stands out for its coveted properties from the combination of wheat and rye, as it inherited lodging resistance, response to fertilizer and an increased florets number per spike from wheat, whereas it got resistance to reverse environmental conditions, tolerance to abiotic stresses and an increased spikelets number per spike from rye, Two major factors contributing to the potential for increased triticale yield are the structural combination of more spikelets in rye and more florets in wheat, This unparalleled combination allows triticale to adapt to varied environments and produce high yields, making it an significant crop for human consumption and animal feed (Suhovici et al., 2025).

Triticale has showed a more harmonious response to environmental conditions changing compared to wheat, making it more flexible to climatic changes due to its high photosynthetic rate and water-use efficiency, which boosts productivity in a varied environmental circumstances. (Méndez-Espinoza et al., 2019). Furthermore, triticale proteins' high mineral contain and intrinsic amino acid composition were significantly contributed to their nutritional value (Sokol, 2009). Due to protein and energy insufficiencies, a significant portion of the world's population suffers from

malnutrition and disease; the incidence of malnutrition-related diseases is predicted to rise from 147,672,757 cases in 2019 to over 160 million cases in 2044 (Jiang et al., 2023). The importance of plant proteins utilizing in human nutrition is highlighted by the significant greenhouse gas emissions from livestock farming because of the reliance on animal proteins (Albaladejo, 2023). The cultivation of triticale crop and the necessary progressions in their agricultural technology should be prioritized to treat nutritional insufficiencies and promote modern trends in healthful food consumption. This includes agricultural applications such as seed priming, planting dates and rates, the application of various types of fertilizers, spraying with growth regulators or micronutrients, and other applications that enable the plant to demonstrate its genetic and physiological capabilities to the highest level required for achieving food security. For the reasons mentioned above, the nutritional value of triticale will be highlighted, along with the possibility of replacing some wheat with triticale. This will be achieved by identifying their nutritional value and comparing their most important morphological characteristics and resistance to abiotic stresses, given the need to develop healthier foods while simultaneously utilizing other grains such as triticale.

**Comparison between the nutritional value of wheat and triticale grains**

Wheat (*Triticum aestivum* L.) is the largest cultivated crop and plays a key role in global agricultural food supply chains (FAOSTAT, 2021). It is one of the oldest grains cultivated by humans and the most common type of grain worldwide. In addition to their valuable chemical composition, the main aim of cultivation is to produce varieties with high grain yield, superior baking qualities, high nutritional value, and high disease resistance. Due to variations in farming methods and climate, studies have revealed notable differences in chemical composition of wheat grains. (Khan and Zeb, 2007). Although wheat grains contain a relatively low percentage of protein (11.38%), they are of great importance as a food source for humans and animals, especially in less developed countries where bread and pasta are staple foods (Shewry, 2009; Sura and Al-Hilfy, 2022a). Furthermore, wheat consumption represents about 19% of the calories in the global human diet and is used worldwide for bread production. Pasta and other products, Therefore, one of the main aspirations for cereal cultivation is to obtain varieties with higher protein content, but this is difficult to achieve due to its inverse relationship with cereal productivity (Biel et al., 2020).

Triticale has a role to play in the growing health food market and in the development of new grain products. As a hybrid of wheat and rye, it is designed to combine high yield potential, good grain quality, multiple food uses, higher disease resistance, and greater tolerance to harsh environmental conditions. Nutritionally, the chemical composition of triticale grain is closer to wheat than to rye. Triticale grain contains slightly higher levels of most nutrients and a starch content similar to wheat and higher than that of rye (61%, 60%, and 54%, respectively). A notable characteristic is its protein content, which ranges from 12% to 17%, while wheat contains 10% to 14% protein.

Triticale is therefore 15–20% higher in protein than wheat. High digestibility is another characteristic of triticale protein (Salmon, 1984; Golenkov, 1985; USDA, 2018; Kamanova et al., 2023).

Triticale flour has a very varied and high-quality chemical composition, suggesting that it could be used in place of whole wheat flour in the production of food and beverages (Zhu, 2018). Some contemporary triticale varieties have a chemical composition that is appropriate from a technological and nutritional standpoint, making them suitable raw materials for the production of flour and bread, according to an analysis of the chemical composition of various triticale grains, flour, and bread. Traditional wheat-based products manufactured in many countries suffer from deficiencies in minerals and vitamins, and their nutritional and biological value can be enhanced by fully or partially replacing wheat flour with nutrient-rich triticale flour (Vasiliev, 2018; Sachko et al., 2020; Siddiqui et al., 2022). Although its bread-making potential is limited, triticale grain is characterized by its high content of essential amino acids such as lysine and threonine, and its rich mineral content, including essential elements like calcium, phosphorus, and potassium, which are vital for consumer health, This makes them nutritionally superior to wheat (Tables 1 and 2). As a result, they can be used to make bread and are a good substitute or addition to other grains in animal feed and human nutrition, due to the low gluten content of triticale flour, it is added to wheat in a proportion ranging between of 10–30% (Yaseen et al., 2007; McGoverin et al., 2011).

**Table 1.** Mineral content of wheat and triticale grains per kilogram of dry matter (Zhang et al., 2010 and Biel et al., 2011)

| | **Triticale** | **Wheat** |
|---|---|---|
| | **Macronutrients (g)** | |
| Potassium | 4.70 | 4.14 |
| Phosphorus | 3.85 | 3.44 |
| Sodium | 0.17 | 0.17 |
| Calcium | 0.40 | 0.37 |
| Magnesium | 1.10 | 1.51 |
| | **Micronutrients (mg)** | |
| Zinc | 25 | 32 |
| Iron | 37 | 39 |
| Copper | 3.4 | 7.4 |
| Manganese | 26 | 48.8 |

**Table 2.** Wheat and triticale cereal protein's amino acid content (g 16 $g^{-1}$ nitrogen) (Biel et al., 2009 and Biel et al., 2016).

| | **Tritical** | **Wheat** |
|---|---|---|
| Lys | 2.56 | 1.89 |
| Met+Cys | 3.43 | 2.77 |
| Met | 1.55 | 1.29 |
| Cys | 1.88 | 1.48 |

| | | |
|---|---|---|
| Thr | 2.99 | 2.25 |
| Ile | 3.51 | 2.39 |
| Trp | 0.90 | 1.02 |
| Val | 4.71 | 3.30 |
| Leu | 6.35 | 5.82 |
| His | 1.99 | 1.90 |
| Phe+Tyr | 7.43 | 5.77 |
| Phe | 4.44 | 3.68 |
| Tyr | 2.99 | 2.09 |
| Arg | 5.41 | 4.19 |
| Asp | 6.27 | 4.67 |
| Ser | 3.88 | 3.61 |
| Glu | 29.42 | 33.12 |
| Pro | 8.59 | 7.29 |
| Gly | 3.91 | 3.36 |
| Ala | 3.85 | 2.58 |

**The potential to improve food security by substituting triticale for wheat:**

Studies comparing wheat and triticale are crucial for a number of reasons. First, they shed light on variations in productivity brought about by phenotypic traits and the crop's capacity to adjust to different environmental circumstances, which is very important for making sure people have enough food during climate change. Second, they help people understand how triticale and wheat vary in terms of nutrition, which helps breeding programs that want to improve crop quality and quantity. Third, these studies emphasize triticale's potential to improve the environment, sustain land production, maintain soil health and fertility, reduce nutrient leaching, support biodiversity, and decrease greenhouse gas emissions. So, inclusive comparative analyses are required.

The prospect of replacing wheat with triticale and enhancing food security stems from the following reasons:

**1. High productivity is due to:**

**1. 1. Triticale morphological traits:**

Triticale's spike, which is a structural combination of the phenotypic characteristics of wheat and rye, is accountable for its high productivity. According to Celestina et al. (2023), wheat spikes have 20–25 spikelets, while rye spikes have 50–60. The triticale spike is multi-spikelets and multi-flowered, two important components in boosting productivity reinforcement. The wheat spike is distinguished by polyflora. Moreover, triticale is a remarkable crop for human consumption and

animal feed because of this special combination, which enables it to adapt to vary environments (Suhovici et al., 2025). Many researches have clarified that triticale excelled wheat in a many of phenotypic characters that are decisive for raising yield, including spike length and spikelets number. The spike length in triticale often reaches 15 cm and is usually umbrella-shaped and has awns, with 30-40 spikelets, whereas the spike length in wheat reaches 12.13 cm and the number of spikelets is 25.6 in each spike (Sokol, 2014; Khashan et al., 2021).

Additionally, triticale superiority wheat in terms of the 1000-grains weight (up to 50.20 g), spikes number (675.2 spikes per $m^{-2}$), grains number (62.56 grains $spike^{-1}$), and the plant height (up to 171.6 cm, depending on the variety). Wheat, on the other hand, has a weight of 1000 grains (up to 45.103 g), a spikes number (up to 512.50 spikes per $m^{-2}$), a plant height (up to 98.29 cm, depending on the variety), and a grains number of 51.25 grains $spike^{-1}$ (Al-Hassan et al., 2014; Dhahi, 2017; Al-Hakam and Abdul-Alwahid 2024; Cui et al., 2025; Deli and Alag, 2025).

The increasing of grain yield of triticale is attributed to its higher total grains number and a larger 1000-grain weight. Cui et al. (2025) observed significant correlations among growth traits and grain and forage yields of triticale. Their findings clarified that the grain yield was positively correlated with 1000-grains weight and spikelets number per spike, indicating that higher grain weight and a greater spikelets number contribute to an increase grain production. Plant height is also positively correlated with grain yield and forage yield. This may be duo to that the taller plants are able to synthesis the dry matter and increase grain and green forage production. A positive correlation was also observed between the quantity of grain yield and forage yield, that indicating that the selecting genotypes with high grain yield is suitable for producing a large forage yield.

**1. 2. Adaptation and resistance to environmental conditions:**

Farokhzadeh et al. (2022) explained that the stability of triticale productivity in various environments exceeds the stability of wheat productivity, as triticale pure lines show good adaptability and stable productivity in diverse conditions.

Generally, triticale outperforms wheat in terms of yield potential and adaptability to various environments, especially in water-limited conditions. Water use efficiency plays a crucial role in determining the productivity and resilience of both crops. Triticale is more efficient in water use than wheat, which is a major advantage in water-limited environments. This efficiency is related to high chlorophyll contain in triticale's leaves, the efficiency of the photosynthesis process of the leaves, and the maximum rate of electron transport, which contribute to it outperform productivity in both well-irrigated and water-limited conditions (Méndez-Espinoza et al., 2019).

Grain and biological yields of wheat under suitable conditions reach 5.055 and 16.51 tons $ha^{-1}$ respectively, while they are decreasing to 3.24 and 12.13 tons $ha^{-1}$ respectively under drought (Dhahi, 2017). These findings are consistent with Mohammed and Kadhem (2017), who indicating a decrease

in productivity under drought stress as a result of reduction the yield components such as the spikes number and 1000-grain weight. However, triticale demonstrates its ability to adapt to unsuitable environments such as semi-arid environments and its ability to produce high-quality grains and fodder, with grain production reaching 6.92 tons $ha^{-1}$ and total green fodder production reaching 29.78 tons $ha^{-1}$ according to varieties. Therefore, triticale is a valuable dual-purpose crop due to its ability to achieve sustainable grain and fodder production in semi-arid conditions and its superior ability to adapt and maintain consistent and stable production in those conditions where maximizing land productivity and conserving resources are necessary (Cui et al., 2025).

Researches indicate that Triticale shows a yield advantage over wheat in arid regions due to its high water use efficiency, large root system, and drought resistance (Ayalew et al., 2018; Giunta et al., 2019).

Méndez-Espinoza et al. (2019), when comparing the productivity of triticale cultivars Aguacero-INIA and spring wheat cultivars Pandora-INIA and Domo using data from ten regions in 2004 and 2005 (eight Mediterranean and two temperate) under conditions of well irrigation and water scarcity, demonstrated a significant difference (according to regression equations) in productivity based on the environmental index (Figure 1). The results of the regression analysis revealed that triticale possessed a higher regression coefficient than wheat, indicating greater adaptability and yield stability under varying environmental conditions. Such stability may contribute to its Greater Productivity, even in difficult environments. Large differences in slope ($p < 0.01$) and crossovers ($p < 0.0001$) between crops confirm triticale's superior adaptability and crop stability. Triticale also outperforms wheat in grain yield due to its larger grain size. This highlights triticale's potential as a energetic crop in diverse and challenging environments.

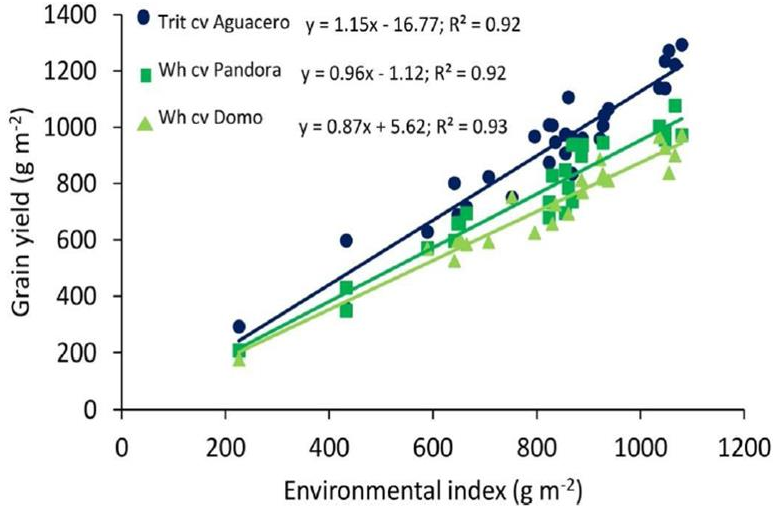


**Figure 1.** Triticale productivity (Aguacero-INIA variety) and spring wheat (Pandora-INIA and Domo varieties) in relation to environmental index (Méndez-Espinoza et al., 2019)

When comparing grain productivity between triticale and wheat under moderate and nitrogen-stressed conditions, triticale was observed to be superior in grain production by large differences of 606 and 795 kg $ha^{-1}$ respectively, which indicating that its strong productivity performance, especially under nitrogen-stressed conditions, makes it a strong candidate for difficult growing conditions with balancing total productivity and nutritional value (Tamagno et al., 2022).

Triticale generally gives a higher grain yield compared to wheat, especially in Mediterranean environments where water scarcity is common in the spring and summer. In contrast, wheat production and protein content are negatively affected by drought, as there is a significant decrease in grain and protein yield under drought conditions (Wan et al., 2022; Xu and Sun 2024).

Studies have documented triticale's ability to adapt to various environmental stresses, including salinity. In salinity-affected areas, triticale varieties showed stable productivity and greater adaptability compared to wheat. When four promising triticale varieties (PI-429166, PI-429152, PI429101 and Syria-1) were evaluated under three salinity levels (15.6, 30.1, and 33.5 ds $m^{-1}$ soil salinity), no significant differences were found between the triticale varieties in grain yield, straw yield, or harvest index (Abu et al., 2017; Farokhzadeh et al., 2022).

**2. Nutritional value of triticale grains:**

Wheat is distinguished by its high grain yield, high nutritional value, and suitability for many products. It also exhibits some degree of stress resistance. A key objective in cereal cultivation is to develop varieties with higher protein content, which is difficult to achieve in wheat due to its inverse relationship with grain productivity (Shewry, 2009; Biel et al., 2020). Therefore, triticale can be used as an alternative crop because it offers a higher protein and more balanced amino acid content. Although triticale's chemical composition (carbohydrate and starch content) is closer to wheat's, the grains contain a higher percentage of vitamins, especially B vitamins, and a higher content of minerals, particularly potassium, calcium, and phosphorus. These qualities make it more nutritious than wheat (Tables 1 and 2). Wheat flour can be partially replaced with Triticale flour in several applications:

**2. 1. bread making**

Wheat bread contributes approximately 50% of the daily calorie intake in many developing countries. Whole-grain wheat bread is important for nutrition due to its carbohydrates, protein, dietary fiber, vitamins, minerals, and antioxidants. In addition, gluten and gliadin proteins play a key role in the quality and desirable characteristics of wheat bread, such as its high palatability, loaf rise, and the colorful bubbles on its surface (Elsahookie et al., 2021). The nutritional value of cereal protein is due to amino acid content. Therefore, interest in triticale as a grain crop has increased in recent years due to its balanced amino acid profile, high glutamic acid and proline content, and 15-20% higher lysine levels compared to wheat. The high yield potential and valuable nutritional characteristics of triticale

have led to its rapid expansion across different countries and continents, with increasing incorporation into the bread-making and animal feed industries (Suhovici et al., 2025). The texture and nutritional value of the bread are enhanced by substituting some of the wheat flour with triticale flour. Triticale flour can be mixed with wheat flour at a ratio of 30% to produce bread with a similar quality, appearance, and color of the crumb as well as a pleasant taste and aroma. (Pena and Amaya, 1992)

**2. 2. Other food products**

The incorporation of triticale flour in sponge cake formulations results in products with improved sensory properties and increased nutritional and biological value relative to cakes made solely from wheat flour. Their increased concentration of vitamins, especially B vitamins, minerals, protein, and essential amino acids is what gives them this advantage. Sponge cakes made from triticale flour have twice the levels of threonine and valine and four times the levels of isoleucine, lysine, and tryptophan, according to an analysis of the protein's biological value (Table 3), offering substantial benefits to consumers. Whole grains, flakes, and flour are commercially available triticale products for human consumption, but they are usually only found in specialty health food stores (Biel et al., 2020).

**Table 3.** A comparison of the nutritional content of sponge cakes made with triticale and wheat flour (Taraymovych and Lobanova, 2024).

| Composition | Value of the final product per 100g | |
|---|---|---|
| | **Triticale sponge cakes** | **Wheat Sponge Cake** |
| Protein (g) | 11.6 | 9.9 |
| Fat (g) | 20.6 | 25.1 |
| Carbohydrate (g) | 46.1 | 44.56 |
| Dietary Fiber (g) | 13.3 | 11.5 |
| Biological Value (%) | 71 | 57.55 |
| Energy | 497 | 598 |
| | Minerals (mg) | |
| Potassium | 1470 | 325.5 |
| Calcium | 1062 | 43 |
| Magnesium | 206 | 40.8 |
| Phosphorus | 1610 | 215 |
| Iron | 3.4 | 4.7 |
| | Vitamins (mg) | |
| E | 0.90 | 5.21 |
| B6 | 0.73 | 0.45 |
| B3 | 3.60 | 0.58 |

| | | |
|---|---|---|
| B2 | 1.50 | 0.50 |
| B1 | 0.65 | 0.40 |
| | Amino Acids | |
| Valine | 1822.5 | 880 |
| Isoleucine | 1812 | 690 |
| Leucine | 2539.2 | 1283.4 |
| Lysine | 1836.8 | 4679.7 |
| Methionine | 1054.8 | 423 |
| Threonine | 1567.2 | 508.8 |
| Tryptophan | 507.2 | 144.8 |
| Phenylalanine | 3291.2 | 1130.8 |

**3. Environmental impact:**

**3. 1. Preserving the fertility and health of the soil:**

The different influences of triticale and wheat on soil health and fertility are primarily due to their difference nutrient requirements and residue management practices. Triticale has been shown to be more efficient at using nitrogen than wheat, especially under nitrogen-deficiency conditions, leading to lower nitrogen fertilizer requirements. Furthermore, triticale can absorb a significant amount of nitrogen and phosphorus from soil, aiding in nutrient management and reducing the risk of nutrient loss. Triticale cultivation also improves soil organic carbon content and maintains soil health and fertility (Tamagno et al., 2022; Glaze-Corcoran et al., 2023; Jańczak-Pieniążek, 2023).

**3. 2. Biodiversity:**

Triticale cultivation can positively impact biodiversity and agricultural systems because it exhibits greater resistance to biotic stresses, thus reducing the need for chemical inputs such as pesticides and fertilizers (Tamagno et al., 2022). This minimizes negative impacts on soil organisms and improves biodiversity. Furthermore, its cultivation provides food sources for these organisms, supporting the ecosystem (Glaze-Corcoran et al., 2023). In contrast, wheat cultivation requires higher chemical inputs such as large amounts of fertilizer and the use of more herbicides, insecticides and fungicides, which negatively affects biodiversity (Jańczak-Pieniążek, 2023).

**3. 3. Sustainability and Reduced Greenhouse Gas Emissions.**

Triticale has been shown to produce a higher grain yield compared to wheat when using the same inputs such as water and fertilizer (Tamagno et al., 2022). This resource efficiency translates into reduced greenhouse gas emissions associated with fertilizer production or application to the soil (Oldfield et al., 2018). Adopting triticale promotes sustainable agricultural production, improves

resource use efficiency, preserves soil health and biodiversity, and reduces greenhouse gas emissions (Xu and Sun, 2024).

Leaf area is indeed a fundamental element in environmental health. It is the primary source for maintaining active photosynthesis, thus absorbing atmospheric carbon dioxide and converting it into biomass. The flag leaf contributes a significant percentage of grain yield, reaching 35.29%. Furthermore, it plays an economic role by consuming atmospheric carbon dioxide and releasing oxygen and water vapor, which helps reduce greenhouse gas levels and improves environmental sustainability. Triticale has a flag leaf area of 51.69 $cm^2$ compared to wheat (38.51 $cm^2$) (Racz et al., 2022, Sura and Al-Hilfy 2022b, and Hassouni and Al-Freeh 2025).

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