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REVIEW

Tritordeum: a versatile and resilient cereal for Mediterranean agriculture and sustainable food production

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Abstract
This review paper provides an in-depth analysis of × Tritordeum [(Ascherson et Graebner)], a novel cereal crop with promising agronomic, nutritional, and economic potential. Through a comprehensive examination of the crop's agronomic characteristics and management requirements, we highlight its adaptability to Mediterranean climates, resilience under changing environmental conditions, and potential applications in the food industry, such as breadmaking and pasta production. We also discuss the role of digital agriculture technologies in optimizing tritordeum cultivation and their potential impact on agricultural practices. Furthermore, we assess the opportunities and challenges associated with tritordeum's integration into the agricultural economy and production systems, emphasizing its potential to contribute to a more sustainable and health-conscious food system. By offering a holistic understanding of tritordeum's attributes, this review serves as a valuable resource for researchers, agronomists, food manufacturers, and policymakers interested in exploring the potential of this innovative cereal grain.

Keywords Tritordeum · Mediterranean basin · Digital agriculture technologies · Sustainable food production

Abbreviations

N	Nitrogen
IPM	Integrated pest management
IWM	Integrated weed management
RTK GPS	Real time kinematics global positioning system

Introduction

Tritordeum [× Tritordeum (Ascherson et Graebner)] is a new cereal developed through crosses between durum wheat (*Triticum turgidum*) and wild barley (*Hordeum chilense,* Roem et Schultz) (Martín et al. 1999; Cabo et al. 2014; Martinek et al. 2001). It's a man-made species, second to triticale and resulted by following a similar hybridization path (Fig. 1). Tritordeum is not a GMO and it is cultivated mainly for human consumption. This crop has piqued the interest of researchers, agricultural professionals, and food manufacturers due to its unique properties. Tritordeum boasts an enhanced nutritional profile with higher fiber, unsaturated fatty acids, and antioxidants compared to traditional wheat varieties (Arora et al. 2022; Ballesteros et al. 2003; Vadim et al. 2020).

Although plant breeders have made attempts in crossing wheat and common barley (*H. vulgare*) since early 1900 (Farrer 1904), that led in the production of many fertile derivatives such as addition, substitution, and translocation lines, no fertile amphiploids were produced from these crosses (Molnár-Láng et al. 2014). The same dead end occurred when using wild barley relatives except the case of *Hordeum chilense,* Roem et Schultz, a species native only in Chile and Argentina which gave fertile amphiploids. During the 1970s, first amphiploid (octoploid tritordeum) between *H. chilense* and *T. aestivum* (cv. Chinese Spring) was obtained at the former Plant Breeding Institute in Cambridge (U.K.) but again fertility was extremely low (Martin

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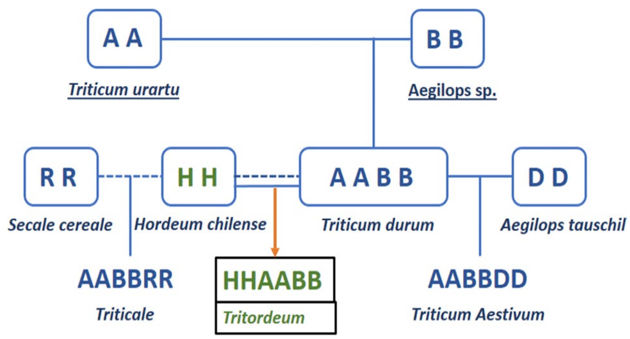


Fig. 1 Diagrammatic representation of the synthesis and breeding of tritordeum

and Chapman, 1977). On the contrary, hexaploid tritordeum developed during the same period at Spain's Instituto de Agricultura Sostenible (IAS) by using durum wheat as parental material (*H. chilense* × *T. turgidum* conv. durum, $2n = 6x = 42$, $H^{ch}H^{ch}AABB$,) showed a low frequency of aneuploids, a wide variation in rate of growth, and good fertility (Martin and Sanchez-Monge Laguna 1982). It took more than 40 years of research since the development of those early hexaploids and uncountable backcrosses before launching the first commercial variety of tritordeum in 2010 (CPVO database).

Tritordeum combines the favorable traits of wheat and barley, offering nutritional benefits and enhanced environmental sustainability (Suchowilska et al. 2021a, b; Martín et al. 1999; Cubero et al. 1986). Requiring less water and fertilizer, tritordeum minimizes its agricultural impact while exhibiting resistance to various diseases and pests, enhancing resilience, and broad cultivation potential (Kakabouki et al. 2021; Bertola et al. 2021; Castro et al. 1998; Bottrel et al. 2018; Alvarez et al. 1992). Its versatility in food products such as bread, pasta, and pastries has spurred market demand (Mattera et al. 2017; Visioli et al. 2020). Preliminary research suggests tritordeum may have lower gluten levels, potentially serving as an alternative for those with gluten sensitivity, although it remains unsuitable for individuals with coeliac disease (Sánchez et al. 2021; Vaquero et al. 2018; Comino et al. 2016; Sánchez-León et al. 2018). Tritordeum's ongoing research aims to optimize its agronomic properties, enhance nutritional value, and expand food industry applications, presenting a promising and versatile crop for future sustainable and health-conscious food production.

In this review, we aim to provide a comprehensive overview of tritordeum, a novel cereal crop with promising agronomic, nutritional, and economic potential. Our objectives are to: (1) examine the agronomic characteristics and crop management requirements of tritordeum, (2) explore its adaptability to Mediterranean climates and soils as well as its resilience under changing environmental conditions, (3) discuss its various applications in the food industry, such as breadmaking and pasta production, (4) highlight the role of digital agriculture technologies in optimizing tritordeum cultivation, and (5) assess the opportunities and challenges associated with tritordeum's integration into the agricultural economy and production systems. By examining these aspects, we hope to provide a better understanding of tritordeum's potential to contribute to a more sustainable and health-conscious food system.

Agronomic characteristics

Tritordeum exhibits several agronomic characteristics that make it an attractive option for sustainable agriculture, particularly in arid and semiarid regions (Martín et al. 1999; Kakabouki et al. 2021; Cubero et al. 1986). It is well-adapted to Mediterranean climates, thriving in high temperatures and water scarcity (Kakabouki et al. 2020; Villegas et al. 2010). One of tritordeum's primary advantages is its efficient use of water, attributed to its *Hordeum chilense* parent, which thrives in water-limited environments (Martín et al. 1999; Gallardo et al. 1993; Alvarez et al. 1992). Additionally, tritordeum demonstrates higher tolerance to heat stress compared to conventional wheat varieties, making it suitable for cultivation in regions with high temperatures (Villegas et al. 2010; Rodríguez-Quijano et al. 2016; Vaquero et al. 2018). The allohexaploid genome structure of bread wheat, which shares similarities with tritordeum's genetic makeup, contributes to the adaptability of these crops to diverse climatic conditions (International Wheat Genome Sequencing Consortium (IWGSC)). Tritordeum is tolerant of a range of soil types, though well-drained soils with good fertility are optimal for its growth (Kakabouki et al. 2021). This genetic adaptability allows tritordeum to flourish in environments with limited water resources and fluctuating temperatures, making it a promising crop for regions affected by climate change and increasing aridity.

Another notable agronomic characteristic of tritordeum is its resistance to various diseases and pests, which can reduce the reliance on chemical pesticides and promote sustainable farming practices (Alvarez et al. 1992). For instance, tritordeum shows resistance to leaf rust, yellow rust, and Fusarium head blight, which are common diseases that affect wheat crops (Rubiales et al. 2001; Alvarez et al. 1992; Comino et al. 2016). This resistance is thought to be a result of the genetic diversity introduced by the wild barley parent, *Hordeum chilense* (Nevo et al. 2010; Martín et al. 1999). Furthermore, tritordeum's robust root system enables it to better withstand the attack of soilborne pathogens and nematodes (Bertola et al. 2021; Smiley et al. 2017).

In terms of yield, tritordeum has shown potential for competitive grain production, with yields comparable to those of traditional wheat varieties (Martin et al. 1996; Moragues et al. 2006a, b). Yields are expected to be further improved by developing new varieties with improved threshing ability which is limited due to brittle rachis (Martin et al. 1998) of early commercial varieties, as breeding programs have focused on overcoming that disadvantage with promising new advanced lines already available (Kakabouki et al 2020).

Tritordeum's genetic makeup allows for a wide range of adaptability, enabling its cultivation across different climatic conditions and geographical regions (Martín et al. 1999; Ávila et al. 2021). While the development and optimization of tritordeum are still ongoing, its agronomic traits, such as water and nutrient-use efficiency, heat tolerance, disease and pest resistance, and adaptability, demonstrate its potential to contribute significantly to the sustainability and resilience of agricultural systems (Visioli et al. 2020; Rodríguez-Quijano et al. 2016; Rubiales et al. 2001).

Uses and applications

Tritordeum has attracted interest in the food industry due to its nutritional properties and versatile processing characteristics, which make it suitable for various applications (Kakabouki et al. 2021; Vaquero et al. 2018; Ballesteros et al. 2003; Nocente et al. 2021) (Table 1). A study by Martin et al. (1999) demonstrated that tritordeum bread boasted a 12.8% protein content, higher than that of traditional wheat bread. This high protein content, coupled with its lower gluten content compared to wheat (Vaquero et al. 2018), has led to tritordeum's increased use in the cereal food sector and bread production (Kakabouki et al. 2020a, b, c, d). Additionally, recent research indicates that tritordeum malt shows promise as an additive in the brewing industry, further broadening this alternative crop's potential applications (Zdaniewicz et al. 2020).

Table 1 Nutritional content of tritordeum grains (Suchowilska et al. 2021a, b; Atienza 2023; Kakabouki et al. 2020)

Seed quality characteristics	Value
Protein content (%)	11.7–17
Fat (%)	2.2
Ash (%)	2.5
Fiber (%)	1.7
Gluten (%)	27–37
Carotenoid content ($\mu g.g^{-1}$)	5.8
Total tocols ($\mu g.g^{-1}$)	30.2
Beta-glucans (% dry matter)	0.6

Tritordeum, has been demonstrated to positively impact the cooking quality, texture, and sensory properties of pasta in the production process (Romano et al. 2021; Visioli et al. 2020; Ballesteros et al. 2003; Giordano et al. 2019). Additionally, brewers' spent grain (BSG) serves as a valuable ingredient for pasta fortification. In a study by Nocente et al. (2021), the nutritional potential of pasta made with einkorn and tritordeum BSG was investigated, revealing that the inclusion of BSG from both cereal types significantly increased protein, total dietary fiber (TDF), and glucan content. This enhancement effectively improved the nutritional profile of the pasta.

Beyond bread and pasta, tritordeum has been utilized in the production of pastries, cookies, and other baked goods, where it has been shown to improve the nutritional value and sensory characteristics of these products (Russo et al. 2022; Gomez et al. 2010; Ballesteros et al. 2003; Giordano et al. 2019). For instance, a study by Giordano et al. (2019) found that cookies made with tritordeum flour had 1.8 times higher total phenolic content and exhibited a 2.5 times greater antioxidant capacity compared to cookies made with traditional wheat flour.

As for functional foods, a study by Suchowilska et al. (2021a, b) reported that tritordeum grains contained up to 1.5 times more phenolic acids, 2.4 times more flavonoids, and 3 times more tocopherols than common wheat, contributing to its antioxidant capacity. Tritordeum has also been explored as a potential ingredient in gluten-reduced products due to its lower gluten content compared to conventional wheat (Vaquero et al. 2018; Comino et al. 2016; Sánchez-León et al. 2018; Gil-Humanes et al. 2010; Mena et al. 2012; Prandi et al. 2017). For example, a study by Nitride et al. (2022) found that tritordeum flour, bread, and digested bread contained approximately 55% fewer R5-epitopes compared to soft wheat, highlighting the potential benefits of tritordeum as an alternative to traditional wheat products.

Tritordeum offers a wide range of uses and applications in the food industry, with evidence supporting its nutritional benefits, sensory properties, and versatility in product formulation. Its potential in breadmaking, pasta production, pastry, and baked goods, as well as functional foods and gluten-reduced products, highlights its promise as a novel and sustainable cereal grain for a healthier and more environmentally friendly food system. Novel crops (including tritordeum) have been suggested to benefit food systems and enhance food security (Mavroeidis et al. 2022).

Optimizing crop management

Tritordeum requires tailored management practices to optimize growth, yield, and performance. These practices encompass fertilization, irrigation, pest control, disease management, and weed management.

Adequate nitrogen (N) fertilization is crucial for tritordeum, and it is recommended to follow guidelines similar to those for wheat and barley (Kakabouki et al. 2021; Landolfi et al. 2021; Marschner 2012). Split applications of N and the use of N inhibitors, like nitrification inhibitors or urease inhibitors, can improve N use efficiency and reduce nitrogen losses (Khan et al. 2013; Abalos et al. 2014; Lassaletta et al. 2014; Byrne et al. 2020). Organic amendments, such as compost or cover crops, can further enhance soil fertility, resulting in increased yield and improved crop quality (Diacono & Montemurro 2011).

Tritordeum is drought-tolerant (Fig. 2) and water-use efficient, making it suitable for regions with limited water resources (Kakabouki et al. 2021; Villegas et al. 2010). Proper irrigation management is essential for optimal growth and yield, with deficit irrigation strategies maximizing water-use efficiency while maintaining productivity (Fereres & Soriano 2007). Advanced irrigation technologies, such as drip or subsurface drip irrigation, can further improve water-use efficiency by up to 90% compared to traditional methods (Howell 2003).

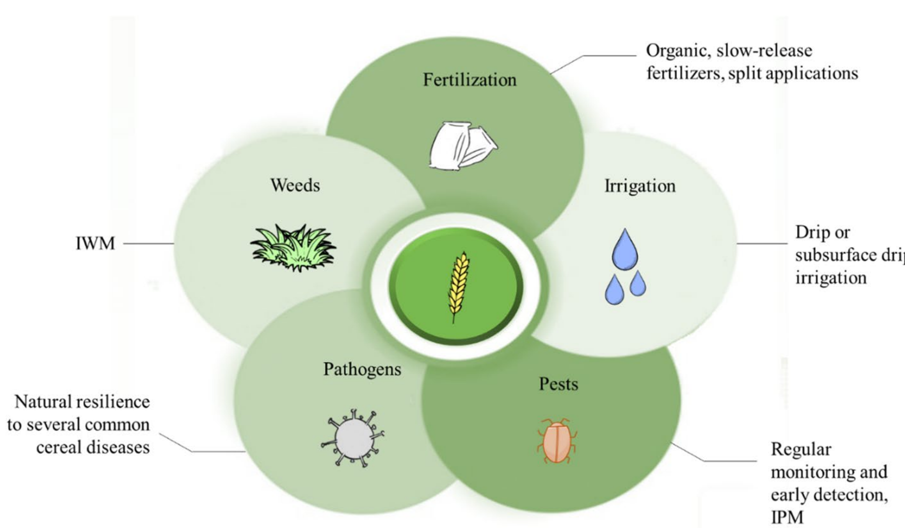
Effective pest management in tritordeum involves regular monitoring and early detection of pests, such as aphids, cereal leaf beetles, wireworms, and armyworms (Smiley et al. 2017; Bottrel et al. 2018). Integrated pest management (IPM) practices, including crop rotation, intercropping, and biological control methods, can suppress pest populations and reduce the need for chemical control, resulting in decreased pesticide use (Pimentel et al. 1993; Zehnder et al. 2007; van Lenteren 2000). Selective and low-risk pesticides should be used as part of an IPM program to minimize nontarget effects and pesticide resistance, which can lead to a reduction in pesticide application (Grafton-Cardwell et al. 2008).

Tritordeum exhibits natural resistance to several common cereal diseases, such as leaf rust, stem rust, powdery mildew, Fusarium head blight, and barley yellow dwarf virus (Martin et al. 1996; Moragues et al. 2006a, b; Rubiales et al. 2001). However, it is essential to maintain vigilant disease monitoring and implement integrated disease management strategies to ensure tritordeum's long-term health and productivity. Following these strategies has been shown to reduce disease severity (Campbell & Madden 1990; Dalla Marta et al. 2005; Cicogna et al. 2005).

Effective weed management in tritordeum should follow practices similar to wheat and barley production (Chhokar et al. 2012). Integrated weed management (IWM) strategies, combining cultural, mechanical, and chemical methods, can help reduce herbicide reliance and minimize the risk of herbicide-resistant weed populations, leading to a huge reduction in herbicide use (Gianessi 2013; Liebman & Gallandt 1997). Crop rotation and cover crops can suppress weed growth and improve soil health, further promoting tritordeum's growth and competitiveness, and can result in to a reduction in weed biomass (Teasdale et al. 2007). Continuous monitoring of weed populations and scouting for emerging herbicide-resistant weeds are essential for effective weed management and have been shown to increase weed control efficacy by up to 30% (Owen & Beckie 2015).

In conclusion, tritordeum cultivation requires a comprehensive understanding of the crop's needs and appropriate management practices to optimize its growth, yield, and performance. By employing best management practices in fertilization, irrigation, pest control, disease management, and weed management, tritordeum can become a successful and sustainable cereal crop in regions with limited water resources and challenging environmental conditions (Fig. 3). These tailored management practices have the potential to significantly reduce input costs, minimize environmental

Fig. 2 Experimental fields of tritordeum as dry crop in central Greece (photo by D. Beslemes)



impact, and contribute to the overall sustainability of agricultural production systems.

The adaptation of tritordeum in Mediterranean areas and climatic conditions

Tritordeum has demonstrated remarkable adaptability to Mediterranean regions, thriving in characteristic climatic conditions such as high temperatures and water scarcity (Kakabouki et al. 2020; Villegas et al. 2010). In a study by Yousfi et al. (2010), tritordeum displayed a yield advantage over durum wheat under drought conditions, emphasizing its enhanced performance in water-limited environments. Similarly, Kakabouki et al. (2020) showcased tritordeum's adaptability to dry conditions in Mediterranean climates and its yield advantage over existing commercial varieties. As a hybrid of durum wheat and wild barley, tritordeum inherits a high degree of drought tolerance and water-use efficiency from its wild barley parent, *Hordeum chilense* (Villegas et al. 2010; Martín et al. 1999). This makes it an ideal crop for Mediterranean areas where water resources are limited, and agricultural production is threatened by increasing aridity due to climate change (Basso et al. 2013; Lobell et al. 2005).

Moreover, tritordeum's resistance to diseases and pests in Mediterranean environments is evident in its ability to withstand the two primary aphid pests of cereals, the greenbug (*Schizaphis graminum* Rond.) and the Russian wheat aphid (RWA, *Diuraphis noxia* Mordvilko) (Castro et al. 1998). Tritordeum amphiploids exhibit genetic resistance to both aphid species, with some lines even more resistant than their parental wheat line (Castro et al. 1998). The crop's adaptability to Mediterranean environments is also reflected in its resistance to common regional cereal diseases and pests, such as yellow rust (*Puccinia striiformis*) and powdery mildew (*Blumeria graminis*) (Rubiales et al. 2001). Furthermore, tritordeum presents fewer α-gliadin allergenic epitopes than modern wheat cultivars, making it a potentially better option for individuals with gluten sensitivity (Landolfi et al. 2021). This lower frequency of celiac epitopes in tritordeum, compared to old and modern wheat, is likely due to the absence of a D genome (Landolfi et al. 2021). This resilience, combined with relatively low input requirements, makes tritordeum a viable and sustainable alternative to traditional cereal crops in Mediterranean areas. Cultivating tritordeum in these regions can help farmers mitigate the impacts of climate change, reduce input costs, and contribute to more environmentally friendly agricultural practices (Kakabouki et al. 2020; Mavroeides et al. 2022).

In a study by Kakabouki et al. (2021), the authors assessed seven alternative crops and concluded that tritordeum is suitable for the Mediterranean Basin and could facilitate the implementation of Green Deal in the Mediterranean Member-States. This hypothesis was based on the reduced-input requirements of the crop that the literature suggests. Therefore, the climate impact of the crop could be significantly lower than the respective one of other major grain crops such as wheat (Kakabouki et al. 2021). As the European Union aspires to significantly reduce the use of agrochemicals (fertilizers, pesticides, herbicides, etc.) by 2030 in order to mitigate climate change, the adoption of such crops could be a viable solution for the fulfillment of its current agri-environmental objectives.

Tritordeum in the era of digital agriculture technologies

Tritordeum can greatly benefit from the implementation of digital agriculture technologies to enhance its cultivation and management. Digital agriculture technologies, such as drone imagery, RTK GPS, and satellite images, can facilitate precise monitoring of crop growth, irrigation, fertilization, and pest control (Chawade et al. 2019; Zhang et al. 2018; Liakos et al. 2018). While there are limited studies focusing specifically on tritordeum and digital agriculture technologies, the experience gained from other cereal crops, such as wheat and barley, can be applied to tritordeum cultivation (Thenkabail 2003; Godwin et al. 2003; Zhang et al. 2002;

Fig. 3 Key points of an optimized crop management in tritordeum

Sankaran et al. 2015). These technologies can provide essential information for farmers, helping them optimize decision-making processes and improve overall crop management (Mulla 2013; Wolfert et al. 2017).

Drone imagery and multispectral satellite data can be used to assess crop health, estimate yield potential, and detect biotic and abiotic stresses (Hassan et al. 2019; Lelong et al. 2008; Gitelson et al. 2005). These remote sensing technologies can be particularly useful for tritordeum cultivation, as they can assist in monitoring water-use efficiency and identifying areas in need of targeted irrigation or fertilization (Moran et al. 1997; Bian et al. 2019). Additionally, the use of RTK GPS technology in precision agriculture enables the accurate application of agrochemicals and machinery guidance, reducing input costs, and minimizing environmental impacts (Chawade et al. 2019; Zhang et al. 2002, 2018; Griffin et al. 2008). By integrating digital agriculture technologies into tritordeum cultivation, farmers can optimize input use, reduce production costs, and increase overall sustainability (Basso et al. 2013; Zhang et al. 2012).

Future research on tritordeum and digital agriculture technologies can explore the development of crop-specific models and algorithms to further enhance tritordeum management. Combining remote sensing data with ground-based information, such as soil properties and weather data, can improve the accuracy of yield forecasts and management recommendations (Candiago et al. 2015; Virnodkar et al. 2020; Lobell et al. 2005; Benedetti & Rossini 1993). As tritordeum continues to gain popularity as a sustainable cereal crop, embracing digital agriculture technologies can help ensure its successful cultivation and contribute to global food security (Shiferaw et al. 2011; Foley et al. 2011).

Tritordeum's potential in agricultural economy and production: opportunities and challenges

Tritordeum offers numerous economic and production advantages that could transform the agricultural landscape, particularly in areas with challenging growing conditions such as the Mediterranean region (Ballesteros et al. 2003; Martín et al. 1999). In a study by Villegas et al. (2010) tritordeum showed a grain yield increase under rainfed conditions compared to durum wheat, highlighting its drought tolerance and potential to enhance agricultural productivity in water-scarce environments.

Its pest and disease resistance have also been documented, making tritordeum a promising option for agricultural economies in Mediterranean environments (Castro et al. 1998; Rubiales et al. 2001). This resilience, coupled with reduced-input requirements, positions tritordeum as a viable and sustainable alternative to traditional cereal crops, with the potential to mitigate climate change impacts, lower input costs, and foster environmentally friendly practices (Kakabouki et al. 2020; Mavroeides et al. 2022). Moreover, tritordeum's lower allergenic potential offers added value for consumers with gluten sensitivities (Landolfi et al. 2021).

The potential of tritordeum in the food industry is gaining traction, with a rising market demand for tritordeum-based products. This is evident in the emergence of several companies across Spain, Italy, and France that have started producing tritordeum-infused bread, pasta, and pastries (Visioli et al. 2020; Giraldo et al. 2010). These innovative products have been met with enthusiasm from consumers, as they offer a unique and nutritious alternative to traditional grain products. A study conducted by Vaquero et al. (2018) revealed that tritordeum bread not only achieved high overall acceptability scores, but also performed comparably to conventional wheat bread. This positive reception highlights tritordeum's potential to become a more widely embraced option within the food industry, catering to the diverse needs of consumers seeking healthier and more sustainable food choices.

Tritordeum's drought tolerance and water-use efficiency make it a promising crop for regions with limited water resources, offering both economic and production advantages (Kakabouki et al. 2021; Villegas et al. 2010). Effective irrigation management is crucial for maximizing growth and yield, and implementing deficit irrigation strategies can maintain productivity while optimizing water-use efficiency (Fereres & Soriano 2007). The adoption of advanced irrigation technologies, such as drip or subsurface drip irrigation, offers additional benefits by improving water-use efficiency compared to traditional methods (Howell 2003). These features present opportunities and challenges for tritordeum's integration into the agricultural economy and production systems.

Despite its advantages, challenges remain in fully realizing tritordeum's potential in agricultural economy and production. There is a need for continued research and development to optimize tritordeum's agronomic properties and explore new applications in food products. The successful integration of tritordeum into the agricultural economy also necessitates increased awareness and acceptance among farmers, food manufacturers, and consumers. Investing in marketing, education, and the development of appropriate supply chains is essential to ensure tritordeum's widespread adoption. By addressing these challenges and capitalizing on tritordeum's unique attributes, this novel cereal grain could significantly contribute to a more sustainable and health-conscious food system, offering economic and production advantages for farmers and food processors in regions affected by climate change and increasing aridity.

Conclusion

In conclusion, this review paper has provided a comprehensive examination of tritordeum, a novel cereal crop with a unique combination of agronomic, nutritional, and economic attributes. Its adaptability to Mediterranean climates, resilience to pests and diseases, and drought tolerance make it a viable alternative to traditional cereal crops in regions facing the challenges of climate change and increasing aridity. The diverse applications of tritordeum in the food industry, ranging from breadmaking and pasta production to functional foods and gluten-reduced products, offer new opportunities for farmers, food processors, and health-conscious consumers. The integration of digital agriculture technologies is poised to further enhance tritordeum's potential, optimizing its cultivation and management practices to maximize yield and sustainability. However, realizing tritordeum's full potential in the agricultural economy and production systems will require addressing key challenges, such as the need for continued research and development, increasing awareness and acceptance among stakeholders, and developing appropriate supply chains.

By embracing tritordeum's unique characteristics and addressing the associated challenges, the agricultural community has the opportunity to contribute to a more sustainable, resilient, and health-conscious food system. This review paper serves as a valuable resource for researchers, agronomists, food manufacturers, and policymakers interested in exploring tritordeum's potential and its implications for the future of agriculture and food production.

Declarations

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