

Exploring alternative cereal flours and their potential for sourdough fermentation: Insights from *Tritordeum* and pseudocereals

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Abstract

Cereal-based foods play an important role in the human diet and represent a source of biological and cultural diversity worldwide, especially when they are fermented. Increasing consumer demand for a nutritional, sustainable and healthy diet has motivated the leavened bakery industries to also direct their attention to new alternative cereal flours to produce products with a better nutritional value, while also ensuring good flavor. In this chapter, we explore the potential of *Tritordeum*, a novel cereal developed from the hybridization of wheat and barley, along with pseudocereals (quinoa, buckwheat and amaranth), which warrant inclusion in diet as main or fortified ingredients. These wheat alternative cereals are not only valuable for their distinct nutritional profiles, including higher protein, dietary fiber, and micronutrient content, but also have potential for the development of new flavor rich, healthy leavened baked goods. Consequently, this chapter delves into the nutritional, functional and technological features of *Tritordeum* and selected pseudocereals considering their strengths and limitations as ingredients to produce leavened baked goods. Furthermore, we review the effect of sourdough fermentation as an emerging, versatile and sustainable process to exploit the nutritional, functional and technological features of alternative cereal flours, and how it improves the sensory and bioavailability of nutrients while mitigating the common challenges, such as anti-nutritional factors and poor rheological properties.



1. Introduction

As the global population grows, so do food security challenges and the demand for sustainable nutrition. Increasing consumer awareness of health-promoting diets has driven interest in functional foods that are sustainable, low in calories and glycemic index (GI), and high in dietary fiber (Rizzello et al., 2017). This has led to the exploration of alternative, protein-rich plants and agricultural by-products to meet nutritional needs. Within the bio-economy framework, alternative flours such as pseudocereals (e.g., buckwheat, quinoa, amaranth) and *Tritordeum* have gained attention for their combined nutritional and functional benefits (Gobbetti, De Angelis, Di Cagno, Polo, & Rizzello, 2020; Haro et al., 2022). Since leavened baked goods are dietary staples, their fortification with such ingredients offers a promising strategy to address sustainability and food security goals (Bartkiene et al., 2016).

Since the early 20th century, cereal breeders have concentrated their efforts on developing interspecies hybrids to produce new cereals with better agronomic performance, enhanced technological qualities, and higher phytochemical content. Among these new hybrid cereals, hexaploid *Tritordeum*

(× *Tritordeum Ascherson et Graebner*) resulting from the cross breeding between wild barley (*Hordeum chilense*) and durum wheat (*Triticum durum*), has emerged as a promising candidate with considerable potential to impact the sustainability of baked goods (Arora et al., 2022). Currently, *Tritordeum* cultivation sums up to 600 ha all over European Union, of which highest producers are Spain (70 %), North Italy (17 %) and Greece (12 %). Its cultivation has also commenced in the Netherlands and Australia (Landolfi & Blandino, 2023).

The cultivation of cereals like oats, barley, and pseudocereals is valuable, but selecting the right varieties is crucial, as many contain both beneficial nutrients and antinutritional factors (ANFs), which can reduce nutrient bioavailability and overall digestibility. In addition, they often exhibit poor rheological properties due to the absence of gluten, resulting in doughs with low elasticity, poor cohesiveness, and weak gas retention capacity (Rakszegi, Papageorgiou, & Rocha, 2023; Sajid Mushtaq et al., 2023). These deficiencies often lead to dense, crumbly textures in baked goods and limit their direct application in conventional baking processes without the aid of structure-enhancing additives. To overcome these limitations, different approaches are utilized, such as the use of food additives (hydrocolloids, modified gums, starches, and protein isolates), technological processing (thermal processing and high-pressure treatments), and biological processes (germination and fermentation) to improve the rheological and techno-functional properties of leavened baked goods (Gobbetti et al., 2020). Sourdough fermentation has gained more attention in modern baking due to its significant impact on flavor and nutritional profile of leavened baked goods (Gobbetti et al., 2019). This process, resulting from the metabolic activity of lactic acid bacteria (LAB) and yeasts, improves sensory and nutritional attributes and increases the shelf life by inhibiting spoilage organisms (Chafai et al., 2023).

The key nutritional benefits of sourdough fermentation include increased bioavailability of minerals through ANFs reduction (e.g., phytic acid, condensed tannins, trypsin inhibitors, and raffinose), reduced GI, and improved protein digestibility (Bondia-Pons et al., 2011; Arora et al., 2021; Ribet, Dessalles, Lesens, Brusselaers, & Durand-Dubief, 2023; Borczak, Sikora, Sikora, & Ćurić, 2013; Costantini et al., 2022). Moreover, sourdough fermentation increases free phenolic compounds with higher antioxidant properties (Rizzello, Coda, Mazzacane, Minervini, & Gobbetti, 2012) and generates bioactive peptides with potential anti-inflammatory and antihypertensive effects (Mohd Roby et al., 2020). The sensory

qualities of sourdough bread are also significantly affected by fermentation because the production of acetic acid and volatile compounds contributes to the complex flavor and aroma. This improves consumer acceptance and encourages the consumption of healthier, less processed bread alternatives, which often contain lower amounts of sugar and fat. From a technological perspective, sourdough fermentation modifies the dough's rheological properties, enhancing its stability and fermentation characteristics. This chapter focuses on the potential benefits of *Tritordeum* and pseudocereals and how sourdough fermentation enhances the nutritional, sensory, and technological features of derivatives leavened baked goods to fulfill the consumer demand for healthier, and nutritionally rich functional foods.



2. *Tritordeum*: A hybrid cereal and potential candidate for sourdough baked goods

2.1 Origin and breeding

In new cereal crops development, *Tritordeum* signifies an advancement, which results from the hybridization of wild barley (*Hordeum chilense*) and durum wheat (*Triticum durum*). This new hexaploid cereal ($2n = 6x = 42$, AABBHchHch) developed in the late 20th century and has gained attention for its agronomic performance and nutritional benefits (Prieto, Ramírez, Cabrera, Ballesteros, & Martín, 2006; Vaquero et al., 2018). This exploits the high crossability of *H. chilense* with various *Triticum* species, enabling the transfer of desirable features such as disease resistance and better nutritional quality into the resulting *Tritordeum* (Ávila, Rodríguez-Suárez, & Atienza, 2021; Castillo et al., 2008; Kakabouki et al., 2020). The breeder aimed for the development of hexaploidy *Tritordeum*, with promising characteristics, including high amounts of antioxidants, improved grain quality, and resistance to biotic and abiotic stresses (Atienza, Avila, & Martin, 2007; Mellado-Ortega & Hornero-Méndez, 2015). The carotenoid content in *Tritordeum* is significantly higher than durum wheat and this trait comes from specific genes from *H. chilense*, particularly located on chromosome 7Hch, which are responsible for carotenoid biosynthesis (Atienza, Martin, & Martin, 2007). This higher carotenoid content of *Tritordeum* not only improves the nutritional profile but also increases its marketability as a health-oriented food product (Mellado-Ortega & Hornero-Méndez, 2012; Vaquero et al., 2018).

Furthermore, *Tritordeum* presents an exclusive gluten composition that may be beneficial for individuals with gluten sensitivities, as it contains less

immunogenic peptides compared to traditional wheat (Ballesteros, Ramírez, Martínez, Barro, & Martín, 2003; Haro et al., 2022). The breeding program of *Tritordeum* has also involved the advanced genomic techniques and use of molecular markers to facilitate the introgression and identification of favorable traits from *H. chilense* into the *Tritordeum* genome (Atienza, Avila, Ramirez, & Martin, 2005; Castillo et al., 2013). This approach has allowed breeders to focus on specific characteristics, such as improved agronomic performance and free-threshing habits, which are essential for the acceptance of crops in commercial agriculture (Atienza et al., 2007; Ballesteros et al., 2003). The successful integration of these attributes has placed *Tritordeum* as a potential alternative source to traditional cereals, particularly in regions where durum wheat is cultivated (Alvarez, Ballesteros, Sillero, & Martin, 1992; Kakabouki et al., 2020).

In the context of climate change, adaptability and sustainability are essential traits for crop development. *Tritordeum* exhibits strong resilience to abiotic stresses, particularly drought and high temperatures, allowing it to maintain stable yields under limited water availability. These characteristics make *Tritordeum* a promising crop for cultivation in arid and semi-arid regions (Agüera, Requena, García-Moreno, Pérez-Priego, & Requena, 2023; Papadopoulos et al., 2024). Apart from this, *Tritordeum* exhibits strong disease resistance, particularly against pathogens such as *Septoria nodorum* and *Fusarium culmorum*, reducing the need for chemical inputs and positioning it with sustainable farming practices. The inclusion of *Tritordeum* in crop rotations can be useful for soil health and biodiversity, which is ultimate support for ecosystem resilience (Papadopoulos et al., 2024).

The cultivation of *Tritordeum* is aligned with the European Union's Green Deal program which promotes sustainable agricultural practices and enhances climate resilience (Kakabouki et al., 2021). By diversifying development systems with alternative crops like *Tritordeum*, farmers can reduce dependence on conventional crops that are more vulnerable to climate-induced stresses, thereby strengthening food security and agricultural sustainability (Papadopoulos et al., 2024).

2.2 Nutritional and functional traits and relevance for sourdough fermentation

A balanced nutritional composition and versatile processing characteristics make *Tritordeum* a suitable candidate for sourdough baked goods. In fact, *Tritordeum*'s richness in complex carbohydrates, proteins, and dietary fiber has led to its increasing use in the cereal food sector, particularly in bread making.

The nutritional comparison of its composition with durum wheat is provided in [Table 1](#). The nutritional profile of *Tritordeum* includes key components that support its suitability for sourdough fermentation. Among these, carbohydrates play a central role in human nutrition and are the primary constituents of cereals, mainly in the form of starch, which serves as a major energy source. Starch consists of the digestible polysaccharides amylose and amylopectin, whose structure and behavior are crucial to the quality of cereals and baked goods. *Tritordeum* contains approximately 65 % starch, slightly lower than that of durum wheat, but still suitable for baking applications. ([Mikulíková, Benková, & Kraic, 2006](#)). The starch composition of *Tritordeum* is influenced by the waxy gene responsible for amylose synthesis, which shows greater similarity to barley than to wheat ([Alvarez, Castellano, Recio, & Cabrera, 2019](#)). Mutations in these genes lead to a decrease in the amylose-to-amylopectin ratio, giving *Tritordeum* flour higher swelling properties and, consequently, a higher loaf volume in leavened baked goods, a crucial physical quality parameter in the baking industry ([Martin, Sherman, Lanning, Talbert, & Giroux, 2008](#)).

In addition to its starch composition, *Tritordeum* is a valuable source of proteins. Since its initial breeding stages, its protein content ranges from 11 to 17 % and has consistently been reported as higher than that of both durum and wheat ([Landolfi & Blandino, 2023](#)). *Tritordeum*'s higher protein content consists of approximately 49 % less gluten than wheat ([Haro et al., 2022](#)). This reduction influences the fermentation behavior of dough; however, the presence of low molecular weight glutenin subunits (LMW-GS) in *Tritordeum* contributes to gluten strength, supporting the elasticity and gas retention needed during fermentation ([Yu et al., 2013](#)).

Total dietary fiber (TDF), which includes both insoluble and soluble fibers, is associated with numerous health benefits, including a reduced risk of coronary heart disease, type II diabetes, and obesity. Thanks to their prebiotic effects, dietary fibers also play a key role in promoting gut health and supporting immunomodulatory activity ([Mendis & Simsek, 2014](#)). A high-fiber diet helps maintain a diverse and functional gut microbiome, particularly through the production of short-chain fatty acids (SCFAs), which are essential for intestinal and immune health. Reduced SCFA production has been linked to chronic inflammatory diseases. In this context, *Tritordeum* stands out for its high dietary fiber content, containing approximately 10 % more TDF than both durum wheat and common wheat ([Landolfi & Blandino, 2023](#)). Notably, among its soluble fibers, *Tritordeum* is especially rich in fructans, prebiotic compounds that support

Table 1 Comparison of nutritional composition of Triticordeum and durum wheat.

Compound	Triticordeum	Durum wheat	References
Starch (%)	67	69	Mikulíková et al. (2006)
Protein (%)	14.–17	12.5	Giordano et al. (2019), Kakabouki et al. (2020)
Fat (%)	2–4	4	Landolfi and Blandino (2023)
Ash (%)	2	2	Landolfi and Blandino (2023)
Total dietary fiber (%)	13–14.7	12	Giordano et al. (2019), Landolfi and Blandino (2023)
β -glucan (%)	1.9	1.1	Giordano et al. (2019)
Arabinoxylan (%)	0.7	0.4	Giordano et al. (2019)
Carotenoids content			
Lutin (ppm)	7.9	1.8	Mellado-Ortega and Hornero-Méndez (2018)
Zeaxanthin (ppm)	5.13	2.31	Mattera, Hornero-Méndez, and Arienza (2020)
α -carotene (ppm)	0.1	0.02	Mattera, Hornero-Méndez, and Arienza (2017)
β -carotene (ppm)	2.5	1.0	Suchowilska, Wiwart, Przybylska-Balcerek, and Stuper-Szablewska (2021)

a balanced and healthy intestinal microbiota. Arabinoxylans (AX) are a major class of dietary fiber in *Tritordeum*, contributing both nutritional and technological benefits, particularly in bread-making. AX improves the physicochemical properties of dough and acts as a storage matrix for phenolic acids such as ferulic acid, which enhance both the nutritional value and functional characteristics of the final product (Courtin & Delcour, 2002). *Tritordeum* contains approximately 26 % more total AX than durum wheat, with levels reaching up to 2.15 %.

Another important class of soluble fiber in *Tritordeum* is β -glucan, known for its role in gut health, cholesterol regulation, and weight management. Although *Tritordeum* was developed from a wild barley species, it does not contain more β -glucan than barley but still has higher levels than wheat (Giordano, Reyneri, Locatelli, Coisson, & Blandino, 2019), offering a valuable dietary contribution.

The phytochemical composition of *Tritordeum* has shown to have great potential for the development of healthy food as compared to durum wheat. Its bioactive compounds such as zeaxanthin and lutein are known for their antioxidant properties (Sardella et al., 2023). Additionally, *Tritordeum* exhibits a significant variability in phenolic compounds content, particularly ferulic acid, another potent antioxidant. This difference is generally influenced by genetic factors, which suggest that *Tritordeum* can be selectively bred to enhance its phenolic content consequently, boosting its health benefits particularly in oxidative stress related diseases (Navas-Lopez et al., 2014). A comparative difference between barely, wheat and *Tritordeum* showed that *Tritordeum* grains contained significantly higher levels of soluble phenolic compounds 25 % more than wheat and 46 % more than barley (Landolfi & Blandino, 2023).

2.3 Dough handling properties and fermentation performance

Tritordeum flour exhibits distinct dough-handling properties, primarily influenced by its gluten composition. A key factor is the ratio of gliadins to glutenins, along with the presence of prolamins, a subgroup of storage proteins, which together play a central role in determining the rheological behavior and bread-making performance of the flour (Ronga et al., 2020). Its high storage protein content reflects the combined genetic background of the *Hordeum* and *Triticum* genomes. *H. chilense* is particularly recognized for its ability to accumulate prolamins, which positively affect dough structure and functionality. The genetic variability in prolamins proteins

derived from the *Hordeum* genome enhances *Tritordeum*'s potential as a valuable cereal for bread-making (Landolfi & Blandino, 2023).

The glutenin and gliadin fractions contribute to different rheological properties, creating a balance between dough extensibility and strength, which is essential for optimal handling (Vogt et al., 2023). Experimental trials using eight *Tritordeum* lines to produce bread demonstrated greater dough extensibility, springiness, and shortness compared to wheat-based bread (Alvarez, Ballesteros, Arriaga, & Martin, 1995). In addition, the presence of LMW-GS in *Tritordeum* enhances dough stability and reduces stickiness during mixing and shaping (Girard, Castell-Perez, Bean, Adrianos, & Awika, 2016).

During sourdough fermentation, LAB and yeasts produce organic acids and gases that improve the viscoelastic and rheological properties of the dough (Vrancken et al., 2010). When applied to *Tritordeum*, sourdough fermentation further enhances both nutritional and technological features, such as increased phenolic content, antioxidant capacity, dietary fiber, and free amino acids. Compared to *Tritordeum* breads produced with baker's yeast, *Tritordeum* sourdough breads displayed improved cohesiveness, resilience, and firmness, supporting its suitability for functional bread production (Arora et al., 2022).

Further, the fermentation process influences the water absorption capacity of dough. While increased absorption can improve dough extensibility, it may also cause stickiness, making the dough more difficult to handle (Avramenko, Hopkins, Hucl, Scanlon, & Nickerson, 2020). Therefore, optimization of water content is essential for achieving the right balance between extensibility and handling ease. The use of enzymes can further improve dough handling properties. For instance, the use of xylanases has been shown to modify the structure of AX in the dough, which eventually enhances the dough stability and reduces the viscosity of dough, that in turn leads to improved gas retention and a more uniform crumb structure (Barrera, León, & Ribotta, 2016; Vogt et al., 2023). Additionally, hydrocolloids can enhance the rheological properties of *Tritordeum* dough, improving its handling characteristics by increasing water retention and reducing stickiness (Previtali et al., 2014). Although research on the sourdough fermentation and baking performance of *Tritordeum* is limited (to date only 2 research papers are available), existing studies highlight its potential as an alternative cereal with desirable nutritional and rheological properties, making it valuable for innovative applications in sourdough biotechnology and baking. Its better dough extensibility and appealing bread color, attributed to higher carotenoid content, are particularly noteworthy.



3. Pseudo-cereals

Pseudocereals such as quinoa (*Chenopodium quinoa*), buckwheat (*Fagopyrum esculentum*), and amaranth (*Amaranthus hypochondriacus*) have gained attention for their exceptional nutritional profiles and functional properties in baked goods. Rich in protein, dietary fiber, essential amino acids, and bioactive compounds like phenolic acids, flavonoids, and trace elements, these grains have been linked to the prevention of degenerative diseases. Their naturally gluten-free nature further enhances their relevance in health-oriented food formulations, particularly for individuals with celiac disease or those adhering to gluten-free diets.

Because of these attributes, pseudocereals are increasingly being explored in sourdough fermentation, either as primary ingredients or as fortifying agents, to maximize their nutritional value and technological potential (Table 2). However, one of the main challenges in using pseudocereals for baking is the absence of gluten. Without it, gluten-free doughs, including those made from pseudocereals, tend to have poor viscoelastic properties, leading to denser, less palatable baked products (Alkay, Alkay, Dertli, Kökten, & Durak, 2023; Song, Guo, & Zhu, 2024).

To address these limitations, various technological strategies have been proposed, including the use of hydrocolloids, enzymes, and binding agents such as exopolysaccharides (EPS) produced during fermentation. These interventions have shown promise in improving the texture, structure, and overall quality of pseudocereal-based baked goods (Turksoy, Guzel, & Guzel, 2024; Zand et al., 2018). In this section, the potential of pseudocereals in sourdough fermentation and their contributions to both nutritional value and overall product quality will be explored.

3.1 Quinoa

Compared to conventional cereals, quinoa (*C. quinoa*) has a balanced nutritional profile that includes a wide array of proteins, essential amino acids, dietary fiber, vitamins, and minerals, collectively contributing to its status as a “superfood” (Brito, Chantelle, Magnani, & Cordeiro, 2022; Repo-Carrasco-Valencia & Serna, 2011). Quinoa is noteworthy for its high protein content, which typically ranges from 9 to 23 % depending on the variety and growing conditions (Craine et al., 2023; Vidueiros et al., 2015). The quality of quinoa protein is very impressive due to its balanced amino acid composition, which includes all nine essential amino acids (Razzeto et al., 2019). Specifically, quinoa is rich in Lys and Thr, which are

Table 2 Exploitation of pseudocereals in sourdough fermentation and its effect on final baked goods.

Flours	Starter culture	Effect of sourdough fermentation on final baked goods	References
Quinoa and wheat flour	<i>L. plantarum</i> and <i>L. rossiae</i>	Quinoa sourdough improved the chemical, textural, and sensory features of wheat bread	Rizzello et al. (2016)
Quinoa and rice flour	<i>P. pentosaceus</i>	Addition of quinoa sourdough in gluten free rice breads improved Protein content, texture, color, and shelf-life (6 days)	Franco, Evert, and Van Nieuwenhove (2021)
Quinoa	<i>L. reuteri</i> and <i>L. brevis</i>	Due to antifungal properties of LAB strain the self-life of quinoa sourdough bread increased up to 100 %	Axel et al. (2016)
Quinoa	<i>L. plantarum</i> and <i>Leuconostoc mesenteroides</i>	Higer total phenolic compounds and antioxidant activity	Sergio et al.
Quinoa, hamp and chia seed	<i>L. sanfranciscensis</i>	Sourdough reduced the bread staling and increase bread porosity and overall acceptability	Jagelaviciute and Cizeikiene (2021)
Quinoa, rice, and oat meal	<i>L. plantarum</i>	Addition of quinoa sourdough improved flavonoids, total phenols and increased radical scavenging activity	Chiş et al. (2020)
Quinoa	<i>L. plantarum</i>	Sourdough fermentation decreased phytate and improved the bioaccessibility of minerals	Sergio et al.

(continued)

Table 2 Exploitation of pseudocereals in sourdough fermentation and its effect on final baked goods. (cont'd)

Flours	Starter culture	Effect of sourdough fermentation on final baked goods	References
Buckwheat and wheat flour	<i>L. fermentum</i> , <i>L. plantarum</i> , <i>Lactobacillus vaginalis</i> and <i>Lactobacillus crispatus</i>	Buck wheat sourdough addition improved the nutritional properties, reduced phytic acid contents. Incorporation of buckwheat sourdough also improved the shelf life of wheat bread.	Moroni et al. (2012)
Buckwheat flour	<i>L. plantarum</i> and <i>L. brevis</i>	Sourdough had a significant effect on the mechanical properties of the crumb. Its structure became springier. Overall sensory quality of experimental bread increased, as sourdough reduced bitter aftertaste of buckwheat.	Djowksz and Sadowska (2021)
Buckwheat flour	<i>Weissella cibaria</i>	EPS producing strain significantly improved specific volume and showed good appearance and cross-sectional morphology by improving the rheological properties of dough it also reduced the hardness and moisture loss during storage	Suchowilska et al.
Buckwheat flour	<i>L. plantarum</i> and <i>L. brevis</i>	Crackers with buckwheat sourdough had higher antioxidant activity. Positive influence of sourdough on taste and texture of crackers	Selimović et al. (2017)

Buckwheat and quinoa flour	<i>L. fermentum</i>	Softer, well-aerated crumb, with better crumb structure and larger air area. Quinoa and buckwheat breads showed higher polyphenols and antioxidant activity.	Lancetti et al. (2022)
Buckwheat and brown rice flour	<i>P. pentosaceus</i> and <i>Enterococcus faecali</i>	Sourdoughs fermentation increased the bread volume and decreased the crumb hardness of buckwheat breads as compared to brown rice	Capuani, Behr, Arendt, and Vogel (2014)
Amaranth flour	<i>L. brevis</i> , <i>L. plantarum</i> , <i>L. rossiae</i> and <i>L. sanfranciscensis</i>	Increased GABA, and antioxidant capacity.	Venturi et al. (2019)
Amaranth and wheat flour	<i>L. brevis</i>	Wheat bread supplemented with amaranth sourdough showed the lowest crumb hardness and improved textural features.	Kia et al. (2024)

often limited in conventional cereals (Craine et al., 2023; Razzeto et al., 2019). In addition to its protein content, quinoa is considered a good source of TDF, with levels that generally exceed those found in many conventional cereals. The exact TDF content can vary depending on the variety. (Melini & Melini, 2021; Moawad, Rizk, Kishk, & Youssif, 2018). The fiber content of quinoa has been shown to improve nutrient absorption and gut health, making it beneficial for overall digestive function (Alsuhaibani, Al-Kuraieef, Aljobair, & Alshawi, 2022). Regarding vitamins and minerals, quinoa provides a considerable amount of, iron, potassium, magnesium, phosphorus, and zinc, which are important to maintain the body functions (Granado-Rodríguez et al., 2021). Further, quinoa contain a higher amount of folic acid, (ca. 78 mg/100 g) in comparison to wheat (ca. 40 mg/100 g), while it is also a good source of riboflavin and other B vitamins, vitamin C and vitamin E (Gobbetti et al., 2018). In addition to this, quinoa seeds are rich in phytochemicals which reflect excellent antioxidant capacity and phenolic profiles directly associated with anti-inflammatory responses which reduce the risk of chronic diseases (Stikić et al., 2020; Repo-Carrasco-Valencia, Encina, Binaghi, Greco, & Ronayne de Ferrer, 2010), However, being largely used as an ingredient in baked goods, quinoa presents some technological challenges, such as poor rheological properties (increased firmness, decreased specific volume) and reduced baking quality. These issues are largely due to the absence of gluten and the presence of saponins in bitter quinoa (4.7 to 11.3 g/kg) (Satheesh, Fanta, & Agriculture., 2018), which impart a bitter taste, compromising the sensory characteristics, and preventing the absorption of certain nutrients (Rizzello, Lorusso, Montemurro, & Gobbetti, 2016; Wolter, Hager, Zannini, Czerny, & Arendt, 2014).

Sourdough fermentation has been shown to effectively improve the technological and sensory qualities of quinoa-based baked goods, making it a promising solution for enhancing their overall acceptability (Gobbetti et al., 2020; Rizzello et al., 2016). When *Lactiplantibacillus plantarum* was used as a starter culture, fermentation promoted the formation of organic acids, which lowered the pH and strengthened protein interactions within the dough matrix. The acidification supports the development of hydrogen bonds and other molecular interactions, improving dough cohesiveness and processability (Ceballos-González, Bolívar-Monsalve, Ramírez-Toro, & Bolívar, 2018). Although quinoa lacks gluten, the fermentation can facilitate protein-protein and protein-starch interactions that mimic some aspects of gluten functionality. The presence of LAB during fermentation

can lead to the production of EPS, which can act as a binding agent, and improve the structure of dough (Ramos et al., 2021), stabilize the dough matrix and increase its ability to retain gas (Chiş et al., 2020). Sourdough fermentation can also lead to a more elastic and less brittle dough compared to unfermented quinoa dough, since the process alters the viscoelastic properties improving extensibility and stability (Chochkov et al., 2022; Ma et al., 2022). This is particularly important for gluten-free formulations, where achieving a balance between structure and texture is challenging. Quinoa sourdough fermentation has been shown to significantly impact the fermentation efficiency and rate of carbon dioxide production, primarily due to the unique properties of quinoa and the specific strains of LAB used (Rizzello et al., 2019). Autochthonous quinoa *L. plantarum* and *Limosilactobacillus rossiae* selected for sourdough preparation, allowed a significant increase of total free amino acids, soluble dietary fibers, total phenols, phytase activity, antioxidant activity, and in vitro protein digestibility (IVPD) compared to non-fermented quinoa flour (Rizzello et al., 2016). Similarly, quinoa sourdough fermentation with *L. plantarum* and *Lactiplantibacillus brevis* not only improved the nutritional value but also enhanced the antioxidant activity and reduced ANFs, (Cizeikiene, Gaide, & Basinskiene, 2021).

Furthermore, the balanced nutrient profile of quinoa, including its unsaturated fatty acids and optimal omega-6 to omega-3 ratio, supports the metabolic activities of fermenting microorganisms, thereby enhancing the overall fermentation efficiency and carbon dioxide production rate (Rizzello et al., 2019). When used in combination with other flours, quinoa further improved the nutritional and functional qualities of sourdough products by increasing the availability of fermentable substrates and enhancing both sensory and nutritional characteristics (Çevik & Ertaş, 2019).

3.2 Buckwheat

Buckwheat (*F. esculentum*) was a major crop in some Asian and European countries before the rise of wheat production. In recent years, there has been renewed interest in using buckwheat grains in the food industry with annual production of about 4 million tons worldwide (FAOSTAT, 2016). This minor cereal can grow under harsh condition and on marginal lands, with attractive high protein content (12–18 %) (Mota et al., 2016), which is rich in essential amino acids like Lys and Try often limited in other conventional cereals (Duliński, Starzyńska-Janiszewska, Byczyński, & Błaszczuk, 2017; Sharma, Kumar, & Singh, 2024; Sofi et al., 2023). Buckwheat is a nutrient-

dense crop, rich in essential minerals like magnesium, zinc, copper, and manganese, often surpassing levels found in wheat and rice (Appiani, Rabitti, Proserpio, Pagliarini, & Laureati, 2021; Lu, Murphy, & Baik, 2013; Pisinov et al. 2024; Sofi et al., 2023). Further, diverse minor components with nutritional significance such as polyphenols, D-chiro-inositol and vitamins are also present in buckwheat. Compared to other pseudocereals, buckwheat stands out for its nutritional profile, low GI, and adaptability to various agricultural conditions, making it a sustainable and functional food choice (Ahmed et al., 2013; Naik et al., 2022; Xiang et al., 2022).

Coda, Rizzello, and Gobbetti (2010) developed a sourdough bread using a blend of buckwheat, amaranth, chickpea, and quinoa flours fermented with *L. plantarum*. Compared to conventional wheat bread made with baker's yeast, the sourdough bread showed significantly higher levels of γ -aminobutyric acid (GABA), total free amino acids, phenolic compounds, and antioxidant activity. In addition, it demonstrated improved flavor and greater consumer acceptability. The sourdough fermentation combined with transglutaminase enzyme using *L. plantarum* and *L. brevis* improved the mechanical properties of the crumb of gluten-free buckwheat bread, making it springier and enhanced the overall texture (Diowksz & Sadowska, 2021). Moreover, the sensory quality of the bread was enhanced, as the characteristic bitter aftertaste of buckwheat became less noticeable, resulting in a more palatable product. Incorporating buckwheat sourdough into wheat dough at 10 % and 20 % (w/w) has been shown to strengthen the gluten network, reduce elasticity, and enhance the rheological properties of dough. Hence, resulting wheat breads fortified with buckwheat sourdough had increased polyphenolic content, reduced phytic acid levels and extended shelf life (Moroni, Zannini, Sensidoni, & Arendt, 2012). Finally, sourdough fermentation with *Limosilactobacillus fermentum* strains has been shown to enhance antioxidant capacity, reduce starch hydrolysis, and lower the GI of buckwheat and quinoa-based products (Lancetti, Salvucci, Paesani, Pérez, & Sciarini, 2022).

3.3 Amaranth

Amaranth (*Amaranthus hypochondriacus*), once considered an underutilized crop, has gained renewed attention due to its exceptional nutritional profile, gluten-free nature, and distinct flavor. Its composition varies slightly among species but is generally characterized by high protein content (13–17 % on a dry weight basis), with a notable abundance of essential amino acids such as Lys (0.73–0.84 %) and Trp (0.18–0.28 %) (Bock et al., 2021; Nogoy et al., 2020).

It also provides significant amounts of minerals, including calcium, magnesium, iron, and potassium (Sidorova, Petrov, Perova, Kolobanov, & Zorin, 2023), though the presence of phytates can limit mineral bioavailability. In addition, amaranth is relatively high in fat compared to traditional cereals, with a lipid profile rich in unsaturated fatty acids, particularly oleic and linoleic acids (Marisheva & Beitane, 2023). It also contains numerous bioactive compounds, such as flavonoids and phenolic acids, which have been associated with antioxidant, anti-inflammatory, and other health-promoting effects (Ballabio et al., 2011; Montoya-Rodríguez, de Mejía, Dia, Reyes-Moreno, & Milán-Carrillo, 2014).

Sourdough fermentation has emerged as an effective method to improve both the nutritional and technological potential of amaranth flour. Unlike traditional processing techniques such as soaking, malting, or germination, which have shown limited efficacy in reducing phytates (Rollán, Gerez, & LeBlanc, 2019), fermentation using LAB has been shown to significantly enhance phytase activity, thereby lowering phytate content and improving mineral bioavailability (Rizzello et al., 2016). Moreover, the presence of albumin and globulin proteins in amaranth contributes to dough hydration and elasticity, and fermentation enhances these effects by promoting protein conformational changes and strengthening the protein matrix (Filipčev, Bodroža-Solarov, Pestorić, & Šimurina, 2017). Studies using *L. plantarum*, *Lactobacillus sakei*, and *Pediococcus pentosaceus* demonstrated that fermentation modified the dough's viscosity and elasticity, resulting in textures more comparable to wheat doughs, although the typical elasticity of amaranth remained lower (Sterr, Weiss, & Schmidt, 2009; Houben, Götz, Mitzscherling, & Becker, 2010). Supplementation of wheat bread with amaranth sourdough fermented with *L. brevis* resulted in a softer crumb and improved textural properties (Kia, Sadeghi, Khashaninejad, Zarali, & Khomeiri, 2024). The use of LAB also led to the production of EPS, which acted as binding agents that stabilized the dough matrix and improved gas retention (Ramos et al., 2021). Additionally, higher concentrations of amaranth flour increased the elastic behavior of flour blends, an effect attributed to its protein content, which played a role in dough cohesion and gas retention during fermentation (Badia-Olmos, Laguna, Haros, & Tárrega, 2023). In gluten-free baking, where texture is often compromised by the absence of gluten, the ability of amaranth proteins to hold water and form cohesive networks proved critical for achieving satisfactory dough structure (Różyło, Rudy, Krzykowski, & Dziki, 2015).



4. How sourdough fermentation improves the nutritional and functional benefits of alternative flours

The literature consistently highlights the ability of sourdough fermentation to enhance the sensory, nutritional, textural, and shelf-life characteristics of leavened bakery products (Gobbetti et al., 2014). The metabolic and functional roles of yeasts and particularly LAB in sourdough systems have been well documented, and considerable efforts have been made to define the technological parameters that influence sourdough performance (Gobbetti et al., 2016). Sourdough fermentation offers multiple benefits, especially in the context of pseudocereal-based baked goods. It plays a crucial role in reducing fermentable oligosaccharides, disaccharides, monosaccharides, and polyols (FODMAPs), as well as ANFs such as phytic acid, raffinose, and condensed tannins, which are known to impair nutrient absorption. The use of specific LAB strains enhances the degradation of these compounds, thereby improving digestibility. Additionally, sourdough fermentation increases antioxidant activity, further contributing to the health-promoting properties of the final product. It also elevates levels of soluble dietary fiber, which is more easily metabolized by the gut microbiota, promoting the growth of beneficial microorganisms and enhancing the production of SCFAs. As a result, sourdough fermentation not only improves the nutritional quality of baked goods but also makes them more suitable for individuals with digestive sensitivities (Arora et al., 2021) (Fig. 1).

4.1 Removal of antinutritional factors and mineral bioavailability

Cereals and pseudocereals contain phytic acid, condensed tannins, trypsin inhibitors and raffinose as a main ANFs. Their presence and concentration vary depending on the type of cereal and pseudocereal. Phytic acid (myo-inositol hexasphosphate) is the primary storage form of both phosphate and myo-inositol in cereal grains, nuts, legumes, and oilseeds, making up 1–5 % of their weight (Priyodip, Prakash, & Balaji, 2017). Phytate, a myo-inositol derivative containing six phosphate groups, carries a strong negative charge, which gives it a high affinity for positively charged food components such as minerals and proteins. This allows phytic acid to chelate multivalent cations such as Ca^{2+} , Mg^{2+} , Fe^{2+} , Zn^{2+} , and Mn^{2+} , as well as amino groups in proteins, thereby reducing the solubility and bioavailability of these minerals. Additionally, phytic acid affects starch digestibility

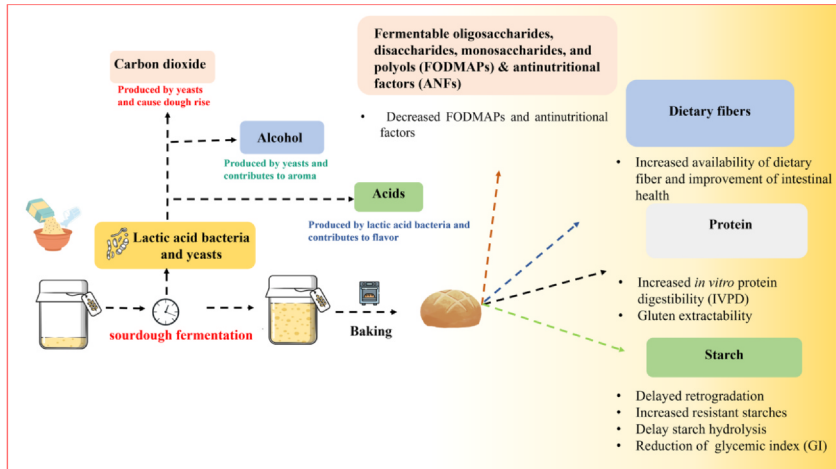


Fig. 1 Graphical illustration of sourdough fermentation showing the metabolic activity of lactic acid bacteria (LAB) and yeasts, which drive biochemical transformations to enhance the nutritional, functional, and attributes of leavened baked goods.

by either binding directly via hydrogen bonds or indirectly by inhibiting alpha-amylase activity. This chelating property of phytate results in anti-nutritional effects and contributes to micronutrient deficiencies (Sharma et al., 2020).

Sourdough fermentation plays a pivotal role in reducing ANFs and enhancing mineral absorption in baked goods, largely due to the metabolic activity of LAB and yeasts (Rizzello et al., 2016). LAB contribute to the hydrolysis of phytic acid through the release of phosphate groups, a process facilitated by phytase enzymes produced by both microorganisms and the activated endogenous phytases in flour. This enzyme activity increases the ionic and soluble forms of minerals, thereby improving their bioavailability (Fig. 2). Additionally, the breakdown of phytate releases myo-inositol, a compound involved in several metabolic pathways (Sharma et al., 2020). The duration and temperature of sourdough fermentation are critical for maximizing phytate reduction. Longer fermentation times have been associated with greater phytate degradation and improved mineral availability. For example, sourdough fermentation with *L. plantarum* for 72 h reduced phytate content by up to 91 %, while also increasing polyphenol content and antioxidant activity (Pejcz, Lachowicz-Wiśniewska, Nowicka, Wojciechowicz-Budzisz, & Harasym, 2023). Similar findings were reported by Taccari et al. (2016), and Casado et al. (2017) further confirmed that optimal fermentation temperatures enhance phytase activity, accelerating phytate hydrolysis.

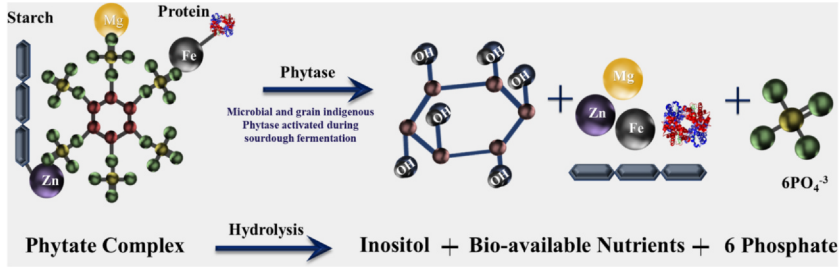


Fig. 2 Schematic representation of phytase activity during sourdough fermentation. Phytase catalyzes the dephosphorylation of phytic acid, release inositol, free inorganic phosphate and bioavailable nutrients. This process reduces the chelating capacity of phytic acid, enhancing the bioavailability of minerals and proteins.

In addition to phytic acid, condensed tannins are another class of ANFs that can interfere with nutrient absorption by binding to dietary proteins and digestive enzymes, reducing protein digestibility and inhibiting zinc and iron absorption. During sourdough fermentation, tannins undergo enzymatic hydrolysis primarily mediated by LAB-produced tannase, which breaks them down into simpler phenolic compounds. This reduces their astringency and improves nutrient availability (Gänzle, 2014). LAB and yeasts can further metabolize tannins as carbon sources, releasing monomeric catechins and other bioavailable phenolics (Poutanen, Flander, & Katina, 2009).

Trypsin inhibitors, another group of ANFs found in cereals and pseudocereals, are also degraded during sourdough fermentation. This occurs through the action of endogenous proteases and proteolytic enzymes secreted by certain LAB strains, which hydrolyze these proteins into smaller, less inhibitory fragments (Huang et al., 2020).

Raffinose, an indigestible oligosaccharide, can cause gastrointestinal discomfort due to fermentation by gas-producing bacteria in the colon. Sourdough fermentation reduces raffinose content through the action of α -galactosidase, an intracellular enzyme that hydrolyzes raffinose into galactose and sucrose, improving digestibility (Teixeira, McNeill, & Gänzle, 2012). LAB strains such as *L. plantarum* and *L. brevis* have been shown to reduce raffinose by up to 64% in legume-based sourdoughs. Overall, sourdough fermentation of whole wheat, barley, chickpeas, lentils, and quinoa flours has led to significant reductions in various antinutritional factors: raffinose (62–80%), condensed tannins (23%), trypsin inhibitors (23–44%), and saponins (68%) (Montemurro, Pontonio, & Rizzello, 2019).

4.2 Protein digestibility and lower glycemic index

Both in vivo and in vitro studies have demonstrated that sourdough fermentation enhances protein digestibility (Rizzello et al., 2019; Ameer, Arora, Polo, & Gobetti, 2022). Most reports show an increase in vitro protein digestibility (IVPD), calculated as the ratio of digested to total protein ($\text{IVPD} = \text{digested protein}/\text{total protein} \times 100$) following enzymatic hydrolysis (Ameer et al., 2022). Additional protein quality indicators, including the chemical score (CS), protein efficiency ratio (PER), and nutritional index (NI), have also been observed to improve during sourdough fermentation. This improvement is largely attributed to LAB-mediated proteolysis, which partially hydrolyzes complex proteins into smaller peptides and free amino acids, thereby enhancing their bioavailability (Chauhan, Gujral, & Kaler, 2024; Orekoya et al., 2021; Ogodo, Ugbogu, Onyeagba, & Okereke, 2019). Furthermore, sourdough fermentation reduces the concentration of tannins and polyphenols, which are known to inhibit protein absorption, particularly in pseudocereals, where these compounds are typically more abundant (Orekoya et al., 2021). The breakdown of these antinutritional factors further contributes to improved protein utilization.

In addition to enhancing protein quality, sourdough fermentation also has a significant impact on the glycemic response of baked products. The glycemic index (GI) is a measure of how quickly carbohydrates in food raise blood glucose levels. According to Harvard Medical School, GI values are categorized as high (≥ 70), moderate (55–69), or low (≤ 55). The glycemic load (GL) complements this by considering both the quality and quantity of carbohydrates consumed (Eleazu, 2016).

Sourdough fermentation has been shown to lower the GI of bread by increasing the levels of resistant starch and slowly digestible starch, which reduce the rate of carbohydrate hydrolysis and the postprandial glucose spike (Demirkesen-Bicak, Arici, Yaman, Karasu, & Sagdic, 2021). Experimental data indicates that both the type of fermentation and the fermentation temperature significantly affect the GI and hydrolysis index (HI) of sourdough products. In these studies, GI and HI decreased while resistant starch content increased, with the greatest reductions observed under optimized fermentation conditions (Demirkesen-Bicak et al., 2021).

Lower-GI sourdough products offer several metabolic benefits, especially for individuals with insulin resistance or at risk of type 2 diabetes. Low-GI diets have been shown to improve glucose and lipid metabolism and normalize fibrinolytic activity (Björck & Elmståhl, 2003). Moreover,

sourdough bread enriched with dietary fiber has been associated not only with improved glycemic response, but also with better sensory attributes, potentially increasing consumer acceptability (De Angelis et al., 2009).

Combining sourdough fermentation with *Tritordeum* or pseudocereal flours can produce bread with both higher protein digestibility and lower glycemic impact, while also offering added health benefits. These include improved antioxidant activity and blood pressure regulation, partly due to the generation of bioactive compounds such GABA and angiotensin-converting enzyme inhibitory peptides during fermentation (Peñas, Diana, Frías, Quílez, & Martínez-Villaluenga, 2015).

4.3 Low fermentable oligosaccharides, disaccharides, monosaccharides, and polyols (FODMAPs)

Irritable bowel syndrome (IBS) is a common functional gastrointestinal disorder, affecting approximately 7–21 % of the global population. Its symptoms include bloating, cramping, and altered bowel habits such as constipation, diarrhea, or both (Canavan, West, & Card, 2014). While gluten is often cited as a trigger, growing evidence also implicates FODMAPs (fermentable oligo-, di-, monosaccharides, and polyols), as contributors to IBS symptoms (Staudacher & Whelan, 2017). Fructo-oligosaccharides (fructans) and galacto-oligosaccharides (GOS) are poorly absorbed and readily fermented by gut bacteria, leading to gas production and bloating. Individuals with IBS are especially sensitive to this fermentation, often experiencing significant discomfort after consuming high-FODMAP foods.

Sourdough fermentation has been exploited to produce low-FODMAP products due to its proven ability to significantly reduce the levels of indigestible oligosaccharides (fructans and GOS), resulting in products more tolerable for individuals with IBS (Graça, Lima, Raymundo, & Sousa, 2021). Several LAB and yeasts such as *L. fermentum*, *Weissella confusa* and *Saccharomyces cerevisiae* have been used for the development of low-FODMAPs sourdough (Ma et al., 2022; Xu et al., 2019). Traditional cereals such as wheat, barley, and rye, commonly used in baked goods, contain high levels of FODMAPs, particularly fructans. In contrast, pseudocereals like quinoa, buckwheat, and amaranth generally have lower FODMAP content, making them more suitable starting ingredient for producing sourdough based baked goods. The extent of FODMAP reduction during sourdough fermentation depends on several factors, including fermentation time and, most importantly, the composition of the microbial community, which plays a key role in effectively lowering

FODMAP levels. In some cases, the microbial species involved in the fermentation process can increase FODMAP levels by converting digestible carbohydrates, such as sucrose and fructose, into FODMAPs. Therefore, microbial strains that specifically can degrade fructan and mannitol are essential. Recent studies have found that the yeast *Kluyveromyces marxianus* effectively degraded excess fructans during dough fermentation. Further, a microbial consortium consisting of *Weissella minor*, *L. brevis*, *L. plantarum*, *Leuconostoc citreum*, *L. fermentum*, and *Companilactobacillus farciminis* has been used to develop sourdough with low FODMAP, with overall 92% decrease in fructan (Menezes et al., 2021). Hence sourdough fermentation with selected pool of LAB is a valuable tool for producing low-FODMAP baked goods (Struyf, Laurent, Verspreet, Verstrepen, & Courtin, 2017). However, it is essential to recognize that carbohydrates like fructans and GOS play a key role in supporting a healthy gut microbiota. Therefore, when developing low-FODMAP sourdough baked goods, the focus should remain on addressing the needs of targeted patients while considering the importance of these carbohydrates.

4.4 Rheological attributes

Sourdough fermentation plays a crucial role in enhancing the texture and sensory properties of baked products, particularly in sourdough bread. Various studies have shown that sourdough fermentation of pseudocereals with traditional cereals flour enhances several textural attributes including hardness, resilience, cohesiveness, adhesiveness, specific volume, crust and crumb color, moisture retention, and overall crumb structure (Ceballos-González, Bolívar-Monsalve, Ramírez-Toro, & Bolívar, 2018; Lancetti et al., 2022). Similarly, a study on *Tritordeum* based sourdough bread has been shown to have greater cohesiveness, resilience, and firmness compared to bread made with baker's yeast, highlighting its potential to enhance functionality and applications in sourdough biotechnology (Arora et al., 2022). One of the primary effects of sourdough fermentation is the alteration of gluten structure. The microbial activity during fermentation leads to the breakdown of proteins, which can improve the extensibility and elasticity of the dough. This results in a softer texture and a more desirable mouthfeel in the final bread product (Škrobot et al., 2022; Terrazas-Avila et al., 2024). Moreover, the fermentation time has also been shown to significantly affect the textural properties of sourdough bread, with longer fermentation times correlating with increased chewiness and reduced hardness (Naji-Tabasi,

Shahidi-Noghabi, & Davtalab, 2023; Terrazas-Avila et al., 2024). This is due to the enhanced gas retention and improved dough rheology resulting from the interactions between glutenin macropolymers and the metabolites produced during fermentation (Singh, Sethi, Gupta, Kaur, & Wood, 2019). It also activates endogenous flour enzymes, such as proteases and amylases, which help further soften the bread crumb. The effect on the textural properties of sourdough baked goods is also LAB strain dependent. One study produced sourdoughs using buckwheat, oat, quinoa, sorghum, teff, and wheat flour with the heterofermentative *L. plantarum* FST 1.7 added at 20 % to a base bread formulation of the same flour type. Compared to control breads, sourdough fermentation significantly improved textural properties, including increased cell volume and bread porosity (Wolter et al., 2014).

EPS produced by LAB during fermentation enhance the texture of sourdough bread, while contributing to the viscoelastic properties of the dough, improving its stability and texture (Galle & Arendt, 2014; Galle, Schwab, Arendt, & Gänzle, 2010; Valerio et al., 2020). The EPS can lead to a more uniform crumb structure and a softer mouthfeel, which are desirable characteristics in baked goods (Casado et al., 2017; Galle & Arendt, 2014). Sourdough bread from buckwheat, quinoa, sorghum, and teff flours with the addition of 20 % sourdough fermented with the EPS producer *Weissella cibaria* MG1 increased crumb porosity compared to control breads. Further, crumb hardness was significantly reduced in buckwheat (−122 %), teff (−29 %), quinoa (−21 %), and wheat sourdough breads (−122 %). While, the staling rate was notably decreased in buckwheat, teff, and wheat sourdough breads (Wolter et al., 2014).

Selecting the right combination of alternative flours, especially gluten-free pseudocereals, with traditional cereal flours is crucial for achieving optimal baking results. While some pseudocereals enhance dough strength, others may reduce it, highlighting the need for careful flour selection to achieve desirable textural properties. *Tritordeum*, with favorable rheological properties like wheat flour, offers a suitable alternative for individuals with gluten sensitivities, as it reduces gluten immunogenic peptides (Nitride et al., 2022; Vaquero et al., 2018).

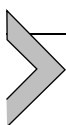
4.5 Sourdough as a tool to improve shelf-life

The shelf life of baked goods, particularly bread, is affected by both staling and microbial spoilage. Microbial deterioration poses a costly challenge, leading to an estimated 5–10 % loss in global bread production. The presence

of mold spores in bakery environments is a major contributor to bread spoilage, creating economic burdens for bakeries and health risks for consumers (Axel et al., 2015). Common spoilage molds include *Aspergillus*, *Endomyces*, *Fusarium*, *Cladosporium*, *Penicillium*, and *Rhizopus*. A natural and effective approach to extend bread shelf life is using sourdough fermentation, as sourdough-associated LAB can produce compounds with antifungal properties (Messens & De Vuyst, 2002). *L. plantarum* demonstrated broad antifungal activity, primarily through the production of 4-hydroxyphenyllactic and phenyl lactic acids being the major inhibitory compounds produced by sourdough LAB (Ryan, Bello, Czerny, Koehler, & Arendt, 2009). Sourdough fermentation with *Fructilactobacillus sanfranciscensis* and *L. plantarum* has been shown to delay bread staling by reducing the rate of starch retrogradation (Corsetti et al., 2000).

In addition to the unpleasant appearance of visible mold growth, fungi can contribute to off-flavor development and produce mycotoxins, which may be present even before mold becomes visibly detectable. Lafuente, de Melo Nazareth, Dopazo, Meca, and Luz (2024) recently investigated the effect of sourdough fermented with *Pediococcus pentosaceus* on fungal contamination. Their results showed that the addition of sourdough significantly extended bread shelf life by reducing contamination from *Aspergillus flavus* and *Penicillium verrucosum* and led to lower levels of mycotoxins.

Alternative flours, particularly those from pseudocereals, are more susceptible to fungal spoilage due to their higher water content and nutrient availability. While research on using sourdough fermentation to extend the shelf life of pseudocereal-based breads is still in early stages, it shows promising potential as a form of bio preservation. Studies suggest that certain LAB strains can degrade contaminants in gluten-free flours while enhancing their nutritional quality. For instance, using *Lactobacillus amylovorus* DSM19280 in quinoa sourdough bread significantly increased antifungal compounds, such as 4-hydroxyphenyllactic acid, improving both shelf life and bread quality (Axel et al., 2015). Similarly, sourdough fermentation with *L. reuteri* and *L. brevis* strains showed enhanced carboxylic acid production, extending shelf life by up to 100% in quinoa and rice breads (Axel et al., 2016). However, another research by Wolter et al. (2014) found that sourdough fermentation did not prolong the shelf life of bread made from buckwheat, oat, quinoa, sorghum, teff, and wheat flour using *L. plantarum* FST 1.7. While sourdough's potential as a shelf-life enhancer is evident, more research is needed to identify novel LAB strains with antifungal properties, particularly for pseudocereal-based and emerging cereals like *Tritordeum*.



5. Challenges and solutions for ensuring the overall quality of leavened baked goods when using alternative flours

5.1 Challenges

The use of alternative flours (*Triticordeum* and pseudocereals) in leavened baked goods present both challenges and opportunities. Cereals and pseudocereals can significantly alter the texture, flavor, and nutritional profile of products, but they also introduce issues related to rheological properties, water absorption, and overall baking performance. Some of the major challenges associated with using alternative flours are listed below:

- The protein composition of alternative flours vary compared to traditional wheat flour. Gluten in wheat flour provides elasticity and extensibility to the dough, but the absence or lower levels of gluten in alternative flours can result in a weaker protein network, leading to reduced strength and gas retention. This often results in denser baked goods with lower volume, particularly when incorporating pseudocereal flours, which may not offer the same structural support as wheat flour (Meneghetti et al., 2019; Portman et al., 2018; Tosin, Olosunde, & Okon, 2024; Setia et al., 2020; Venturi, Galli, Pini, Guerrini, & Granchi, 2019).
- The water absorption capacity of alternative cereal flours, such as those derived from pseudocereals or whole grains, tends to be higher than wheat flour due to their higher fiber contents (Canalis, León, & Ribotta, 2017; Dapčević–Hadnađev, Tomić, Škrobot, Šarić, & Hadnađev, 2022; Sammalisto, Laitinen, & Sontag–Strohm, 2021). This can lead to overly dry or crumbly baked products if not properly accounted for in the formulation. Apart from visual texture defects, these baked goods tend to have high crumb hardness, low cohesiveness, and elasticity and consequently, high brittleness with a pronounced tendency to fracture.
- From a nutritional standpoint, baked goods made from gluten-free pseudocereals, often lack adequate protein, vitamins, and minerals, which is a major concern, especially for gluten-free diets. These products typically contain lower protein levels and insufficient amounts of B-vitamins compared to their gluten-containing counterparts.

5.2 Strategies to counter technological and nutritional challenges

The challenges of using alternative cereal flours in baked goods can be addressed by incorporating various additives and nutritive ingredients to

improve the quality of the product. One effective approach is using hydrocolloids, proteins, enzymes, or emulsifiers to enhance the rheological properties of dough, which can improve texture, moisture retention, and overall quality (Mir, Shah, Naik, & Zargar, 2016).

Furthermore, blending alternative flours with traditional wheat flour can help mitigate some of the negative effects on baking quality. Research indicates that a careful balance of wheat and alternative flours can optimize the nutritional profile while maintaining acceptable sensory qualities (Lagassé et al., 2022; Setia et al., 2020; Tosin et al., 2024). Blending different types of pseudocereals and legume flours, can yield composite flours that maintain desirable baking qualities while improving nutritional content (Aprodu, Bolea, & Banu, 2019).

Lastly, using specific LAB species/strains during sourdough fermentation can enhance the technological and sensory properties of baked goods. For example, fermentation of quinoa and wheat doughs with *Lactocaseibacillus paracasei*, *L. plantarum*, and *L. brevis* resulted in the production of volatile compounds that improved flavor and other technological features. This indicates that choosing the right microbial cultures can be tailored to optimize flavor profiles in baked goods made from alternative flours, thereby appealing to a broader range of consumer preferences (Renzo, Reale, Boscaino, & Messia, 2018). Sourdough fermentation also reduces FODMAPs and ANFs, improves digestibility, increases antioxidant activity, enhances dietary fiber content, and promotes starch hydrolysis. These changes lower GI and improve IVPD, making the final product more nutritious and easier to digest, especially for individuals with digestive sensitivities.



6. Conclusion

The global diversity in dietary habits presents an opportunity to develop foods that meet consumer demands for sustainability, nutrition, and health. *Tritordeum* and pseudocereals, such as quinoa, amaranth, and buckwheat, hold significant potential in this regard. *Tritordeum*, a novel cereal with lower gluten content and higher levels of bioactive compounds, offers health benefits and enhances dough handling, fermentation dynamics, and the sensory attributes of baked goods. Pseudocereals, which are rich in dietary fiber and protein, provide additional nutritional benefits but face challenges in improving rheology, sensory qualities, and eliminating anti-nutritional factors. Sourdough

fermentation stands out as an ideal method to enhance sensory and rheological properties while reducing anti-nutritional factors, making it more sustainable than other treatments like enzymes or additives. Incorporating *Tritordeum* and pseudocereals into sourdough fermentation offers a promising strategy for creating functional, nutritious, and sustainable baked goods.

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