

## Technological and Nutritional Challenges, and Novelty in Gluten-Free Breadmaking: a Review

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The presence of gluten is considered fundamental for successful breadmaking. However, the ingestion of gluten by susceptible individuals has been associated with the development of gluten-related disorders such as celiac disease, wheat allergy, and non-celiac gluten sensitivity. The elimination of gluten from cereal-based baked products has a detrimental effect on the breadmaking process and sensory properties, and raises technological challenges in terms of making good quality leavened bread. The use of non-gluten raw materials changes the rheological behaviour of the gluten-free dough, which may result in different processing performance and associated post-baking quality of the obtained bread. Gluten-free bread tends to have a poor visual texture characteristics, a low nutritional value, reduced mouthfeel and flavour, as well as a shorter shelf-life. The aim of this review is to present the main problems related to gluten-free breadmaking technology and to summarise recent findings in the improvement of the technological, nutritional, and sensory properties of gluten-free bread. A great deal of this review focuses on the development of novel and healthy gluten-free breads formulated with flours, starches, hydrocolloids, and alternative nutrient-dense raw materials, which should fulfil all quality requirements for bakery products as well as meet the needs of celiac consumers.

### INTRODUCTION

Bread is considered a staple food worldwide [Simićet *et al.*, 2018; Wandersleben *et al.*, 2018]. Gluten proteins or, specifically, the gliadin fraction of wheat and the prolamins from other cereals such as barley (hordeins) and rye (secalins) are responsible for the viscoelastic properties of the dough and the bread-baking unique asset [Peña-Bautista *et al.*, 2017]. However, for individuals who suffer from celiac disease (CD) or other gluten-related disorders (such as wheat allergy (WA) and non-celiac gluten sensitivity (NCGS)) even the ingestion of a small amount of gluten can lead to deleterious and serious health risks [Scherf *et al.*, 2016; Bathrellou *et al.*, 2018], which are graphically depicted in Figure 1. A strict and life-long gluten-free diet (GFD) is the only available therapy for patients suffering from CD, and research results showed improvements in both symptomatology and small bowel histology [Haines *et al.*, 2008]. Patients with NCGS and WA also benefit from a GFD, although individuals with WA do not need to restrict rye, barley, and oats from their diet [Pietzak, 2012].

In reality, a complete avoidance of gluten intake is very difficult, due to gluten ubiquity in human foods, hidden gluten sources, and food contamination. Due to the on-going need for gluten-free products, the gluten-free market is growing fast. While a strict adherence to GFD may lead to nutrition-

al deficiencies in the longer term, the absence of gluten has a detrimental effect on breadmaking process and raises technological challenges in making good quality leavened bread [Horstmann *et al.*, 2018]. In fact, the technological and sensory characteristics of gluten-free bread (GFB) are worse than those of conventional gluten-containing bread [Primo-Martín *et al.*, 2006]. In general, gluten-free baked products are characterized by a crumbling texture, pale crust colour as well as a faster staling rate [Gallagher *et al.*, 2003]. Considerable efforts have been made to improve GFB quality: nutrient-dense ingredients, additives with gluten-imitating function and diverse technologies have been studied in the hopes of narrowing the gap between gluten-free and gluten-containing bread [Capriles & Arêas, 2014; Drabińska *et al.*, 2016]. The aim of this review is to provide recent findings in improving the technological, nutritional and sensory properties of GFB.

### CONVENTIONAL VS. GLUTEN-FREE BREADMAKING

Conventional and gluten-free breadmaking are processes that differ substantially in terms of the complexity of formulations used (including main ingredients and amount of water), dough rheological behaviour, and overall quality of the final product [Conte *et al.*, 2016; Morreale *et al.*, 2018a]. In traditional breadmaking, the term “bread” usually refers to a yeast-leavened product or sourdough bread specifically made with wheat flour. The reason why bread is usually made with wheat flour derives from the unique properties of the in-

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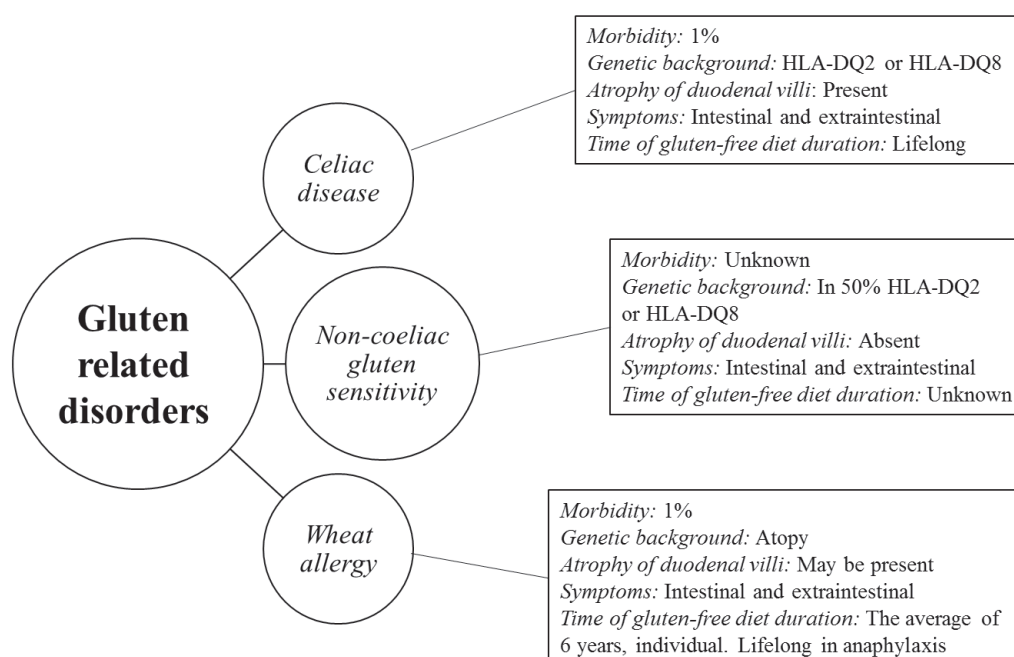


FIGURE 1. Short characteristics of gluten-related disorders.

soluble fraction of wheat protein (gliadin and glutenin) to form, when flour is hydrated and in the presence of mechanical work input, a cohesive viscoelastic mass called a gluten network. Thus, in wheat bread, gluten is considered the main structure-forming complex with an exceptional ability to form a tenacious, extensible, and elastic dough capable of entrapping gas during both proofing and the early stage of baking as well as enclosing starch granules and fibre fragments [Scanlon & Zghal, 2001; Gallagher *et al.*, 2004]. These characteristics of the dough lead to a final bread with a good loaf volume and a typical crumb structure that results in a sponge-like texture, which is highly desirable in the leavened baked goods.

In gluten-free breadmaking, in which the elimination of gluten becomes a necessity, the absence of this continuous three-dimensional protein-starch matrix significantly affects the rheology of the doughs, the production process, and the overall quality of the final breads [Ronda *et al.*, 2017]. Gluten-free doughs, which cannot develop a network similar to traditional breads due to differences in their protein properties, are less elastic and cohesive, and stickier and more difficult to handle than their gluten-containing counterparts [Ronda *et al.*, 2017]. In order to obtain doughs with acceptable consistency and better behaviour during the mixing phase, gluten-free flours/starches require higher amounts of water than wheat flour does. Thus, gluten-free doughs, which have a viscosity more like that of cake batters, are often called batters instead of doughs. The final products, in turn, tend to show some quality defects such as lower specific volume; lighter crumb and crust colour; rough, dry and crumbly texture; and a shorter shelf life [Gallagher *et al.*, 2004; Houben *et al.*, 2012; Jnawali *et al.*, 2016]. Therefore, the production of GFBs, unlike their wheat-containing counterparts, requires different technological solutions. The development of GFB has generally involved the use of complex formulations consisting of a combination of different ingredients

and additives able to imitate the viscoelastic properties of gluten and, consequently, the appearance, quality, and sensory properties of the bread-like products. To this end, due to their negligible structure-building capability, the most common flours and/or starches from different origins (such as rice, corn, potato, and cassava) usually included in GFB formulations, were often combined with binding agents, such as hydrocolloids and protein [Capriles & Arêas, 2014]. Certainly, the most suitable basic ingredient for GFB preparation is rice (*Oryza sativa*) flour. This is probably due to its neutral flavour, white colour, hypoallergenic properties, high amount of easily digested carbohydrates, and its low sodium content [Rosell & Marco, 2008]. However, the use of rice flour in gluten-free breadmaking is also associated with some technological disadvantages. In fact, due to the poor functional properties of its proteins and the low level of prolamins, it is unable to form viscoelastic doughs required to retain the carbon dioxide produced during proofing, leading to a product with low specific volume and a compact crumb [Rosell & Marco, 2008]. However, despite some discrepancies reported in the literature, it seems that not all varieties of rice and their related amylose contents influence the quality of GFB in the same way [Cornejo & Rosell, 2015]. As reported by Kadan *et al.* [2001], the partial replacement (10%) of a long-grain rice variety with a short grain rice resulted in breads with softer crumb and slower retrogradation than those produced with 100% long-grain rice. de la Hera *et al.* [2013] obtained short-grain GFB with higher specific volume and lower hardness values than those of breads made of long rice varieties. On the contrary, Cornejo & Rosell [2015] analysing the breadmaking potential of six long-grain rice varieties, obtained GFBs with characteristics similar to those previously reported for breads made of short-grain varieties. They concluded that the breadmaking properties of rice flour might be more affected by the synergic effect of other factors (particle size,

protein conformation, starch structure) than by the length of the rice grain. Apart from rice flour, corn meal (*Zea mays*) is the second basic ingredient most often used in gluten-free products. In particular, the yellow corn varieties, due to their characteristic yellow colour and distinctive flavour, are more suitable to produce pasta, whereas, the white maize varieties are the flour/starch sources most often used in gluten-free breadmaking [Hager et al., 2012].

Not only starch-containing flours, but also starches from different origins are the main players in providing structure and texture of the manufactured breads [Jnawali et al., 2016]. During the bread baking process, starch is able to bind water and form a gas-permeable structure influencing, in turn, water retention and dough rheology [Houben et al., 2012; Witczak et al., 2016]. In fact, starch granules gelatinize (through granules swelling and partial solubilisation of starch) and form a starch paste able to trap air bubbles [Zannini et al., 2012]. As a result, the addition of starch in GFB formulae (either as a single starch or a composite starch mixture) leads to a product with a higher volume, and a softer, more cohesive and compact crumb structure [Gómez & Sciarini, 2015]. However, it is worth highlighting that not all kinds of starches behave in the same way, as their functional characteristics depend on their origin, particle size, amylose/amylopectin content, water swelling and solubility, pasting and gelling, starch treatment, and interaction with other ingredients [Witczak et al., 2016; Zhang et al., 2017]. However, during food processing, despite the numerous advantages of starch, its native forms show a limited resistance to physical conditions, such as high tendency to retrogradation and syneresis, loss of viscosity (especially at low pH conditions), low thermal stability, and inappropriate rheological characteristics of pastes and gels. For this reason, modifications of starches by chemical reactions or physical methods have been proposed to overcome some of these shortcomings [Witczak et al., 2012; Yousif et al., 2012]. Korus et al. [2009] observed that the partial replacement of corn starch with increasing percentages of tapioca and corn resistant starch preparations led to gluten-free doughs with increased elastic behaviour (increase of both storage and loss moduli, and  $G' > G''$ ) and rheological properties typical of a weak gel ( $\tan \delta > 0.1$ ). The resulting GFBs showed diminished crumb hardness values with the increasing amounts of resistant starch preparations applied. These authors also found that the addition of resistant starch raised total dietary fibre, by up to 89%, as compared to the control samples.

The relatively poor functional properties of the above-mentioned basic ingredients, as well as the necessity to mimic the functionalities of gluten, and the inclusion of other polymeric substances such as hydrocolloids and non-gluten protein, are critical factors in a starch-based system like GFB. Hydrocolloids, also known as food gums, are substances consisting of hydrophilic, long-chain, high molecular weight molecules, including different polysaccharides but also some proteins, such as gelatin [Hoefer, 2004]. When they are incorporated in a water-based system, they exhibit a range of functions, including the primary gelling and thickening, but also emulsifying and encapsulating ones [Hoefer, 2004]. Moreover, the hydrocolloids classified as soluble fibres serve

important physiological functions [Matos & Rosell, 2015]. The addition of hydrocolloids to GFB formulae could have several effects on both intermediate and end products. (a) At the dough level, due to their ability to act as water binders, they raise the viscosity of the system, improve the viscoelastic properties of the dough and increase, in turn, its gas-holding capacity. Furthermore, they affect swelling and gelatinization of the starch granules. (b) At the bread level, due to their ability to reduce moisture loss, they slow down starch retrogradation and extend the shelf life of the products, preserving their overall quality over time. Additionally, they influence other bread quality attributes, such as specific volume, crumb structure, texture, and sensory properties [Lazaridou et al., 2007; Jnawali et al., 2016]. Different types of hydrocolloids of both natural (agar-agar, carrageen, pectin and  $\beta$ -glucan, gum arabic, locust bean gum, guar gum and psyllium fibre) and synthetic origin (synthesized cellulose derivatives: hydroxypropylmethyl cellulose (HPMC), carboxymethyl cellulose (CMC), and methyl cellulose (MC); microbial biosynthetic: xanthan gum) have been proposed as gluten replacers in GFBs [Lazaridou et al., 2007; Schober et al., 2008; Demirkesen et al., 2014; Mohammadi et al., 2014; Naji-Tabasi & Mohebbi, 2014]. However, not all kinds of hydrocolloids behave in the same way. In fact, their interaction with other food polymers, such as starch and protein included in the formulation, the specific hydrocolloid used and its supplementation level (usually up to 2%), as well as the parameter of the process, could change the type and extent of influence exerted on both dough and bread properties [Lazaridou et al., 2007; Rosell & Marco, 2008; Capriles & Arêas, 2014; Jnawali et al., 2016].

#### GLUTEN-FREE BATTER/DOUGH CHARACTERISTICS

The quality of GFBs is greatly influenced by the selection and combination of structural ingredients (mainly polysaccharides) that are able to provide stability to the system (by increasing viscosity), as well as prevent an excessive weakening of the protein/starch/hydrocolloids coherent matrix [Scanlon & Zghal, 2001]. For this reason, in the gluten-free breadmaking process, the development of processable doughs able to stretch in response to the expansion of gases released during fermentation, as well as the formation of dough films able to stretch without rupturing and with sufficient strength to prevent the collapse of the structure, are crucial prerequisites to obtain high quality yeast-leavened products [Singh & MacRitchie, 2001; Mir et al., 2016]. From a rheological point of view, due to the large amount of water usually added in the complex recipes and also the absence of gluten, gluten-free doughs resemble a semiliquid system which greatly varies in terms of consistency, viscoelasticity, and structural networking [Gallagher et al., 2003; Hager et al., 2012]. Findings from selected recent research related to the rheological properties of dough and bread are summarized in Table 1. Różyło et al. [2015] demonstrated that, depending on the type of flour used (corn, rice, and buckwheat flour), the addition of different amounts of water (from 80% to 120%) to the dough can affect the quality parameters (such as specific volume and crumb hardness) of different types of GFBs. In particu-

TABLE 1. Different types of flour/starch and amount of water used in gluten-free breadmaking.

Basic ingredients	Amount of water	Dough properties	Bread properties	References
Corn flour Corn starch Potato starch Rice flour Buckwheat flour	90%, 102%	Dough yield Rheological properties (Rheometer) Leavening properties (Rheofermentometer)	Baking yield Specific volume Sensory evaluation	[Pruska-Kędzior <i>et al.</i> , 2008]
Rice flour Oat flour Quinoa flour Sorghum flour Teff flour Buckwheat flour	120% 95% 90% 90% 90% 85%	Microstructural properties Leavening properties (Rheofermentometer)	Bake loss Specific volume Crumb texture Crumb structure Shelf-life Sensory evaluation	[Hager <i>et al.</i> , 2012]
Short-grain rice flour Long-grain rice flour	80% 110%	Microstructural properties Leavening properties (Rheofermentometer)	Weight loss Specific volume Crumb texture	[de la Hera <i>et al.</i> , 2013]
Corn starch Rice starch Rice flour	44.4%, 44.7%, and 52.7%	Mixing properties (Farinograph, Water absorption) Leavening properties (Rheofermentometer, Image analysis)	Specific volume Crumb structure Colour	[Cappa <i>et al.</i> , 2013]
Rice flour Corn flour Corn starch Quinoa flour	80%		Specific volume Crumb texture Sensory evaluation	[Elgeti <i>et al.</i> , 2014]
Rice flour	150%	Rheological properties (Rheometer)	Specific volume Hardness Sensory evaluation	[Demirkesen <i>et al.</i> , 2014]
Rice flour	70–110%		Weight loss Specific volume Crumb texture Starch digestibility and glycaemic index	[de la Hera <i>et al.</i> , 2014]
Corn flour Rice flour Buckwheat flour	80–120%		Specific volume Hardness Crumb structure Sensory evaluation	[Różyło <i>et al.</i> , 2015]
Rice flour	90–110%	Rheological properties (Rheometer)	Specific volume Hardness	[Mancebo <i>et al.</i> , 2015]
Rice flour	78–141%	Dough extrusion (Texture Analyzer) Rheological properties (Rheometer)	Weight loss Crumb texture Crumb structure Colour Shelf-life	[Ronda <i>et al.</i> , 2015]
Long grain rice flour	110 %		Specific volume Crumb texture Crumb colour	[Cornejo & Rosell, 2015]
Rice flour Potato starch Quinoa flour Buckwheat flour	87%	Rheological properties (Rheometer)	Bake loss Crumb texture Crumb microstructural properties Colour Sensory evaluation	[Turkut <i>et al.</i> , 2016]
Maize flour Rice flour Maize starch Wheat starch Potato starch	100%	Microstructural properties Rheological properties (Rheometer)	Crumb microstructural properties Specific volume Crumb texture	[Martínez & Gómez, 2017]
White rice flour	90–110%	Rheological properties (Mixolab®)	Specific volume Crumb texture Crumb structure Colour	[Morreale <i>et al.</i> , 2018b]

lar, they observed that GFBs made with corn flour required the largest amount of water (120%), while, those made with rice flour required the lowest (80%). The importance of hydration levels in determining the viscoelastic behaviour

of gluten-free dough/batter and influencing the rheological characteristics of the resulting bread was also recently confirmed by Morreale *et al.* [2018b]. In the same study, besides the dough hydration levels, the authors underlined the role

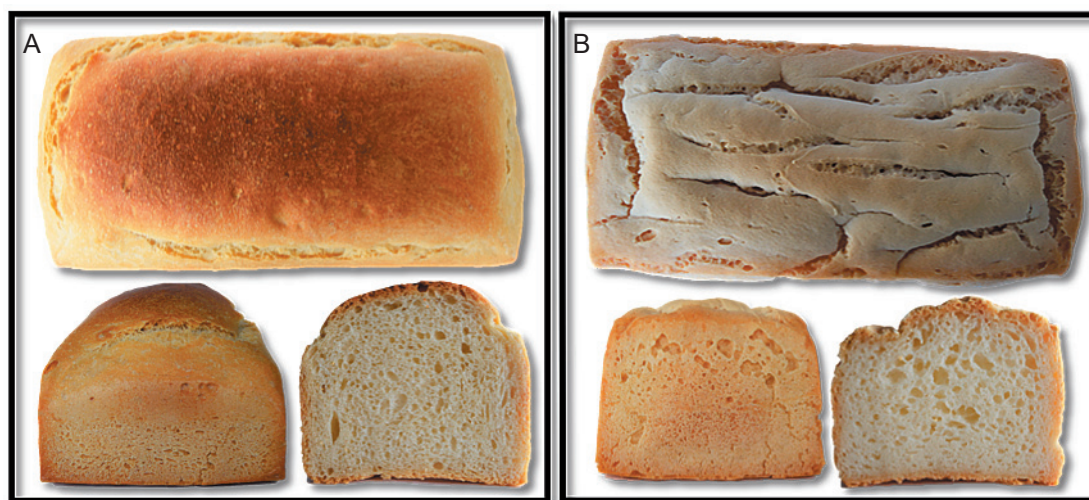


FIGURE 2. Visual appearance of gluten-containing (A) and gluten-free bread (B).

of viscosity (100, 4000, and 15,000 mPa×s) and levels of inclusion (1, 2, 3%) of the hydrocolloid HPMC to improve both batter consistency and some technological parameters of the final products (crumb hardness, cohesiveness, and resilience). The feasibility of improving the rheological properties of gluten-free doughs through the use of different types of hydrocolloids and amounts of water was also explored by many other authors [Cappa *et al.*, 2013; Mancebo *et al.*, 2015; Ronda *et al.*, 2015]. As reported by Pruska-Kędzior *et al.* [2008], the distinct rheological behaviour of gluten-free doughs may also be due to differences in the endogenous protein content and the fractional compositions of the basic ingredients included in the formulation (maize starch and flour, potato starch, rice flour and buckwheat flour). According to the authors, a complex approach involving rheological and fermentographic methods in future studies on gluten-free dough technology could be useful in the development of GFBs with improved sensory profile and prolonged shelf-life. However, although a number of studies have been conducted to characterize the dough/batter rheological properties using both fundamental and empirical analyses, finding reliable predictors able to correlate gluten-free dough rheological properties with the quality of the resulting breads, still remains an important task [Matos & Rosell, 2015]. Matos & Rosell [2013], in an attempt to determine such quality indicators at dough levels, tested seven different gluten-free complex formulations (one based on corn starch, and the other six on rice flour) and evaluated the rheological properties of the dough and the technological and sensory characteristics of the resulting breads. They reported that dough Mixolab parameters showed high correlation coefficients with the physical quality of fresh breads, but relatively low correlations with their sensory characteristics. In particular, a strong relationship was observed between bread crumb hardness and dough consistency during mixing and after cooling. Martínez & Gómez [2017], using the most common types of flours (rice and maize) and starches (maize, wheat and potato) usually included in gluten-free formulae, studied the mechanistic relations among the development of the starch/flour structure, dough rheology, and bread quality. These authors reported

that the structure and morphology of the starch granules and flour particles were the major determinants of dough changes produced during the fermentation and baking phases. The large and compact particles of the flours produced dough with high consistency and breads with volume and textural properties lower than those obtained with starches. In particular, among the starch-based formulations, the small wheat starch granules, which also exhibited the lowest pasting temperature, formed a continuous and uniform starch-hydrocolloid matrix, leading to doughs with a lower consistency but higher holding capacity and, consequently, breads with higher specific volume and better textural properties.

#### QUALITY OF GLUTEN-FREE BREAD

##### Gluten-free bread appearance, texture, and shelf-life

Despite the considerable advances made in improving gluten-free bakery products, some major problems related to their technological and sensory quality must to be overcome. Due to the need of using non-gluten raw materials, the changes observed in the technological properties of gluten-free doughs may result in different processing performance and associated post-baking quality defects of the resulting breads, which tend to have unattractive appearance, in particular pale crust colour with irregular surface, poor mouthfeel and flavour, and a shorter shelf-life [Houben *et al.*, 2012; Jnawali *et al.*, 2016; Conte *et al.*, 2018]. Visual texture is defined as the appearance of the product, ranging from the crust colour to the loaf volume to the crumb grain structure of each single slice of bread [Wang *et al.*, 2013]. The colour of both crust and crumb is known to be one of the most important visual characteristics, which strongly influence consumer choice [Gallagher *et al.*, 2003; Conte *et al.*, 2018]. GFBs, unlike their wheat-containing counterparts, show unappealing and often too white coloration (Figure 2). It may be due to the natural colour of the conventional raw materials included in the formulations [Gallagher *et al.*, 2003; Różyło *et al.*, 2015]. Furthermore, a small amount of proteins and high water contents hamper the browning reaction, which is the main responsible for the formation of brown pigments [Mohammadi *et al.*, 2014].

The specific volume is one of the most important technological parameters of bread quality. However, due to the multiplicity of bread varieties, each of which has its own particular characteristics, the specific volume cannot be considered a quality factor itself. For instance, in the case of breads baked in pans, high values of specific volume, being usually associated with a proper aeration of the bread loaves, are required to obtain products able to satisfy the widest cross-section of consumers. A suitable gas bubble entrapment and a subsequent stabilisation of the foam structure are also fundamental to achieve a fine alveolate structure, in which the resulting pores should be small, regular and spread evenly across the crumb [Elgeti *et al.*, 2014]. It is during baking that the further growth of the gas bubbles previously incorporated during mixing determines dough expansion and, consequently, the final volume and appearance of breads [Scanlon & Zghal, 2001]. Naji-Tabasi & Mohebbi [2015] reported that in formulations based on rice flour, corn flour, and corn starch, the addition of cress seed gum and xanthan gum as gluten substitutes led to breads with higher specific volumes and improved cell area fraction. They also reported that hydrocolloids, by forming thick layer, influenced the stability of the gas cells, leading to more regular and solid pores, especially in breads containing cress seed gum. Furthermore, hydrocolloids (by limiting the diffusion of water) had a positive effect on crumb colour during storage.

Apart from visual texture defects, GFBs tend to have high crumb hardness, low cohesiveness and elasticity and, as a consequence, high brittleness with a pronounced tendency to fracture or crumble [Gallagher *et al.*, 2003]. It is well established that such a mechanical behaviour of GFBs, which is usually described by the above-mentioned physical texture parameters, is strongly influenced by product density and porosity. This implies that, in dough processing, all the aspects that change bread volume and cell structure are also major determinants of the bread texture. Demirkesen *et al.* [2014] studied the effects of the addition of different gums (xanthan, guar, locust bean, agar, MC, CMC, and HPMC) and gum blends (xanthan-guar and xanthan-locust bean) on crumb structure and texture parameters of rice-based GFBs. The authors found that the use of both gum blends and single xanthan, CMC, and HPMC led to breads with homogenous and finer crumb structure in terms of lower porosity and average area of pores, and higher number of pores. They also reported that the hardness, cohesiveness and springiness values were correlated with the internal structure of the crumb. In particular, it was observed that GFBs with softer, more cohesive and elastic crumb, also showed the lower values of porosity, lower average size of pores and higher number of pores. Similarly, de la Hera *et al.* [2014], studying the impact of dough hydration levels (70, 90, and 110%) and particle size distribution (fine and coarse) on the quality of rice-based GFBs, found a strong correlation ( $r = -0.8931$ ;  $P < 0.001$ ) between hardness values and specific volume. In spite of a slightly detrimental effect in the nutritional aspect, better results were obtained with coarse flour and large amounts of water.

Another major disadvantage normally associated with GFBs is the impossibility to keep breads fresh for a longer time. In fact, during storage, baked products undergo a num-

ber of physicochemical changes, ranging from the crumb hardening to the loss of crust crispiness and organoleptic freshness to the gradual decrease in consumer acceptance [Fadda *et al.*, 2014]. These alterations are commonly referred to as staling, which is a complex, but not-well understood process that has been associated primarily with moisture redistribution, starch retrogradation, polymers reorganization, and starch-protein interactions [Fadda *et al.*, 2014]. If, on the one hand, the transfer of moisture from the internal to the external region of the loaf is commonly recognized as mainly responsible for the staling of the crust, on the other hand, staling of the crumb is a more complex phenomenon that involves multiple factors [Gray & Bemiller, 2003]. Certainly, the most widely accepted mechanism involved in the firming of the crumb is the recrystallization of amylopectin. However, also the moisture content and its redistribution among the different constituents of the crumb seems to play a critical role [Gray & Bemiller, 2003; Ronda *et al.*, 2011]. It should be noted that most GFBs, which are often based on pure starches and require an extra amount of water, are more prone to stale than their gluten-containing counterparts. In fact, owing to the absence of gluten, the transfer of moisture may increase, leading to a product with softer crust and firmer crumb [Gallagher *et al.*, 2003; Sciarini *et al.*, 2010]. In an attempt to delay the staling of GFBs, several authors reported different promising strategies, including: (a) the use of enzymes such as  $\alpha$ -amylase and cyclodextrin glycosyltransferase, which are able to partially degrade amylopectin, thus hindering its recrystallization, as well as to modify both protein-starch and protein-protein interactions, respectively [Gujral *et al.*, 2003; Haghghat-Kharazi *et al.*, 2018]; (b) the use of some hydrocolloids such as xanthan, CMC, and HPMC, which are able to decrease the loss of moisture content during storage and, consequently, retard both starch retrogradation and crumb hardening [Mohammadi *et al.*, 2014; Mir *et al.*, 2016]; and (c) the use of sourdough technology [Rinaldi *et al.*, 2017].

#### **Nutritional quality of gluten-free bread**

Another concern regarding GFB is related to its nutritional value. Gluten-free cereal-based products, including bread, are mainly made of starches from different sources or refined flours, they lack several macro- and micronutrients and provide smaller amounts of valuable nutrients needed in a healthy and balanced diet [Gallagher *et al.*, 2004; Martin *et al.*, 2013]. Compared to their gluten-containing counterparts, commercial gluten-free products have a lower protein content, inadequate amount of B-group vitamins [Thompson, 1999; Yazynina *et al.*, 2008], and minerals (including iron, zinc, calcium) [Wronkowska *et al.*, 2008; Saturni *et al.*, 2010]. Besides, gluten-free flours are not enriched or fortified like the refined wheat-based flour or products are on a voluntary or mandatory basis [Department of Health, 1998; Akhtar *et al.*, 2011]. Meanwhile, the enrichment of gluten-free flours in minerals and/or vitamins could increase the nutritional status of CD patients and increase the amount of minerals to the level sufficient for prophylactic or therapeutic use.

Nutritional deficiencies are frequently detected in newly diagnosed and untreated CD patients due to chronic inflam-

mation and malabsorption problem [Wierdsma *et al.*, 2013]. Besides, a GFD which is the only recommended CD treatment may not be nutritionally adequate and well-balanced thus may generate deficiencies that persist in CD patients following this eliminative diet [Saturni *et al.*, 2010; Penagini *et al.*, 2013]. Iron deficiency anaemia [Theethira *et al.*, 2014] and lower bone mineral density [Meyer *et al.*, 2001; Krupa-Kozak, 2014] were frequently determined in CD patients at time of diagnosis. Hallert *et al.* [2002] found a poor vitamins status, in particular lower contents of folic acid and vit. B6 in CD patients on a GFD for over 10 years. In turn, Sdepanian *et al.* [2003] revealed that the mean bone mineral density in adolescents with CD was significantly lower than in the control groups, and that they showed high percentages of magnesium and calcium as well as phosphorous deficiencies.

Recently, a growing number of studies related to gluten-free bakery products besides the focus on the better sensory quality and prolonged shelf-life, pay special attention on the development of products characterised by an improved nutritional quality [Capriles & Arêas, 2014]. Inclusion of microelements into a GFB formulation is one of the promising methods for the improvement of the nutrition value of GFB without compromising its sensory quality. A GFB enriched in calcium was obtained by Krupa-Kozak *et al.* [2011a] who evaluated the effect of the individual and combined addition of calcium caseinate and calcium citrate to GFB formulations. Compared with unfortified control GFB, in breads containing calcium citrate alone (2%) or containing a mixture of calcium citrate and calcium caseinate (1.3% and 0.7%, respectively), a significant increase of calcium levels was determined, which allowed considering the obtained GFBs as good sources of calcium, providing approx. 100–140 mg of calcium per serving. Moreover, the technological and sensory characteristics of calcium-enriched GFBs were favourably modified. In a subsequent study, Krupa-Kozak *et al.* [2012] assessed the suitability of different organic or inorganic calcium sources (calcium lactate, calcium citrate, calcium chloride, calcium carbonate) in GFB formulations with inulin. The best results were achieved with the addition of calcium carbonate, which additionally raised the overall consumer acceptability of GFB. Kiskini *et al.* [2012] compared the effects of iron supplements (ferric pyrophosphate, ferric pyrophosphate with emulsifiers, sodium iron EDTA, microencapsulated ferrous sulfate, and elemental iron) on the sensory and physical quality of iron-fortified GFB (40 mg/kg solid compound). They observed that the electrolytic iron was stable during thermal treatment, and thus its addition caused no adverse changes to GFB. In contrast, authors indicated the limitations of other iron supplements administered into GFB, in particular observed that the addition of ferric pyrophosphate and NaFeEDTA caused undesirable changes in bread, in particular darkening of crust and crumb and a metallic taste.

More often, however, the use of highly nutritious naturally gluten-free ingredients such as pseudocereals, minor cereals, legumes, and protein from various sources has been suggested as an important and dietary method for the improvement of the nutritional value of GFB. However, while the incorporation of such raw materials in gluten-free formulae may have

advantages due to their high nutritional value, there are also disadvantages due to their technological limitations, which can change the appearance, colour, texture, aroma, and taste of GFB [Capriles *et al.*, 2016]. Several excellent reviews summarized the nutritional aspects of fortified gluten-free products, including their glycaemic index and antioxidant capacity [Capriles & Arêas, 2016; Taylor *et al.*, 2016; Tsatsaragkou & Mandala, 2016; Torres *et al.*, 2017]. The recent application and properties of additional ingredients in GFB will be discussed in the following sections of this review.

## HOW TO IMPROVE GLUTEN-FREE BREAD?

In the last few decades, a great deal of attention has been paid to the development of novel and healthier GFBs able to fulfil all quality requirements for bakery products [Capriles *et al.*, 2016]. To this end, the special role of different protein sources has been strengthened and the use of alternative nutrient-dense raw materials and natural compounds has become increasingly popular.

### Proteins of animal and plant origin

To build up a network similar to that formed by gluten in wheat bread production, the inclusion of other polymeric substances such as non-gluten proteins is a critical factor. Although proteins play a functional role in developing bread structure and texture, their inclusion in gluten-free formulae may also confer nutritional benefits to the final products [Ziobro *et al.*, 2013a]. Different types of proteins of both plant (such as cereals, pseudocereals, and legumes) and animal origin (such as dairy proteins and egg albumins) have been used to produce protein-enriched GFBs [Crockett *et al.*, 2011; Ziobro *et al.*, 2013a; Aguilar *et al.*, 2015; Collar *et al.*, 2015].

Dairy ingredients such as caseinates, whey proteins, and skim milk powder were widely used in gluten-free bread-making due to their functional properties, which are similar to these of gluten, and to their high nutritional value, which entails an increase in calcium and protein content and supply of essential amino acids [Stathopoulos, 2008; Nunes *et al.*, 2009]. However, not all kinds of dairy proteins behave in the same way, as they possess different functionalities, which range from the ability of caseinates to stabilize the dough/batter, through the ability of isolated and concentrated whey proteins to form gels, to the high water-holding capacity of high-temperature skim milk powders [Nunes *et al.*, 2009]. Thus, the addition of dairy proteins in GF bread formulae could have several effects on the overall quality of the intermediate and end products: (a) at the dough level, they increase water binding capacity and enhance the handling properties of dough/batter; (b) at the bread level, they increase loaf volume, improve texture, enhance crust colour and aroma, and reduce the staling rate [Houben *et al.*, 2012]. Krupa-Kozak *et al.* [2013] evaluated the effects of the addition (12% and 24%) of four low lactose dairy proteins (calcium and sodium caseinate, dried whey protein isolate, and hydrolyzed whey proteins) on the behaviour of the dough and the quality properties of the resulting GFBs. They found that, although the GFBs exhibited higher protein content at all supplementation levels, breads prepared with the addition

of 12% milk powders where more than 5 times richer in protein than the control one; in addition, their crumb softness, specific volume, crust darkening, and crumb lightness were observed to significantly increase. However, since many newly diagnosed patients with coeliac disease commonly report a secondary lactose deficiency caused by an inadequate secretion of lactase (which is normally produced by the intestinal villi), the use of high-lactose dairy ingredients in the development of gluten-free bakery products must be carefully considered.

Other kinds of proteins which have shown a great potential in gluten-free breadmaking are egg proteins. The addition of egg proteins as gluten replacers is due to their foaming ability, stabilizing effect, and emulsifying properties. However, due to their allergenic character, their use as food products ingredients should be limited or carefully considered [Phongthai *et al.*, 2016].

Another way to include proteins in a GFB formulation is to use various types of legume grains. In fact, legumes offer a high nutritional value, suitable functional properties, and beneficial health effects. They are important sources of protein, whose content ranges from 18 to 25%. Soybeans, however, are unique in that they contain about 35–43% protein [Tharanathan & Mahadevamma, 2003]. Moreover, legume proteins, due to their high content of the essential amino acid – lysine which is often deficient in grain food, as well as a concomitant deficiency of methionine and cysteine, are nutritionally complementary to cereal proteins [Duranti, 2006]. Legumes are also good sources of minerals (such as calcium and iron), vitamins (especially B-group vitamins), and dietary fibre (both soluble and insoluble fractions). In addition, they are identified as low glycaemic index foods [Collar *et al.*, 2014]. When incorporated into food matrices, legume proteins show a range of functional properties, which include foaming, emulsifying, and gelation capabilities as well as texture, water/oil binding capacity, and viscosity [Maninder *et al.*, 2007]. In recent years, proteins from legume sources such as soybean, carob, pea, and lupine have been widely used in gluten-free breadmaking [Marco & Rosell, 2008a; Crockett *et al.*, 2011; Ziobro *et al.*, 2016; Horstmann *et al.*, 2017]. Soy proteins, which are usually added into the bread formulae either as soy protein isolates or high-protein soy flour, have for long been used to improve mechanical behaviour of doughs as well as textural properties, specific volume, and nutritional value of GFBs [Marco & Rosell, 2008b]. However, soy flour incorporation may be curbed by its “beany” flavour. Shin *et al.* [2013] found that the pre-treatment of soy flour can improve not only the flavour but also technological parameters of GFBs. Carob, which is the fruit of the carob tree (*Ceratonia siliqua* L.) (also called locust bean) is cultivated throughout the Mediterranean region for its edible pods. Carob flour is rich in proteins, dietary fibre, micronutrients, and polyphenols [Turfani *et al.*, 2017]. Moreover, it contains caroubin, a water-insoluble protein able to form wheat-like dough due to disulphide bonded high molecular weight proteins, which makes carob an interesting ingredient in gluten-free breadmaking [Smith *et al.*, 2012]. In fact, it was observed that carob germ flour (7%), when mixed with corn starch (93%), HPMC (2%) and water (80%), was able to form viscoelastic dough

similar to that of wheat, resulting in breads with both a higher specific volume and crumb softness [Smith *et al.*, 2012]. Tsatsaragkou *et al.* [2014] used the Response Surface Methodology to optimise the levels of carob flour, resistant starch and water in rice-based GFBs. They reported that the use of 15% carob flour, 15% resistant starch, and 140% water resulted in GFBs rich in fibre (6.10 g/100g) and with softer crumb and improved porosity values. However, Miñarro *et al.* [2012] in their attempt to substitute soya protein with other legume proteins such as pea isolates, chickpea and carob germ flour, obtained opposite results. These authors found that, in spite of good rheological properties, the breads obtained with carob germ flour showed the lowest specific volume, the darkest crumb, and the highest values of hardness during 5 days of storage. On the contrary, the best overall behaviour (higher specific volume and softer crumb during storage) was observed in the breads produced with the addition of chickpea flour, probably due to the good emulsifying stability index of its proteins. Significant improvement in both the technological and the nutritional quality of GFB achieved via incorporation of chickpea flour has been recently reported also by other authors [Ouazib *et al.*, 2016; Santos *et al.*, 2018].

### Pseudocereals

The rekindled interest in some under-utilized and naturally gluten-free plant species such as buckwheat, amaranth and quinoa derives from their excellent nutritional value. In fact, in addition to a superior protein profile, they have high contents of resistant starch, dietary fibre, and micronutrients, such as vitamins, minerals, and phenols. Although the number of gluten-free bakery products made of all three pseudocereals has increased significantly, buckwheat flour remains the most studied ingredient in the development of GFBs. On the contrary, only a few attempts have been made to include quinoa into GFB formulations [Capriles & Arêas, 2014].

Buckwheat belongs to the family *Polygonaceae* and genus *Fagopyrum*, which consists of about 15 species cultivated around the world. However, among them, only two species are utilized for food consumption: *Fagopyrum esculentum* and *Fagopyrum tataricum*, which are also known as common and tartary buckwheat, respectively. The nutritional value of buckwheat flour is highly connected with its protein composition. In fact, contrarily to the true cereals, where the main proteins are glutenin and prolamins, buckwheat proteins are composed mainly of the water-soluble globulins and albumins, which contain high levels of the essential amino acids lysine and arginine, resulting in a well-balanced amino acids composition. Due to that, despite a protein content close to that measured in common cereal grains (12%), buckwheat protein has a high biological value [Alvarez-Jubete *et al.*, 2010a,b; Giménez-Bastida *et al.*, 2017; Tömösközi & Langó, 2017]. Buckwheat is also a source of minor components such as minerals (potassium, calcium, copper, zinc, and manganese), vitamins (B-group and E), and phenolic compounds (hyperin, quercitrin, and quercetin). In particular, among pseudocereals, it is unique in containing the flavonol glycoside-rutin with recognized anti-inflammatory and antioxidant properties [Zhang *et al.*, 2012; Wronkowska *et al.*, 2016; Tömösközi & Langó, 2017]. Lukšič *et al.* [2016], evalu-



ating the impact of sourdough fermentation and thermal processes on the conversion of rutin to quercetin in bread made of common and tartary buckwheat, observed that the combined effects of sourdough fermentation and baking process only preserve quercetin, but not rutin, in tartary buckwheat breads. In turn, Torbica *et al.* [2010] found that the incorporation of different levels (up to 30%) of both husked and unhusked buckwheat flours in rice-based GFBs made the addition of hydrocolloids not necessary for a good development of the dough structure, without detrimental effects on the sensory bread acceptance (except for high levels of unhusked buckwheat flour). They also reported that the addition of increasing amounts of buckwheat flour reduced the starch retrogradation degree of the tested samples, leading to a final product with improved anti-staling properties. Other study assessed the effect of a dehulled and puffed buckwheat flour application at 40% substitution level on the nutritional value of two commercial GFB mixtures [Mariotti *et al.*, 2013]. Authors indicated that the inclusion of 40% dehulled buckwheat flour improved the leavening properties of the commercial GF mixtures. Moreover, the presence of a small amount of puffed buckwheat flour and HPMC limited the diffusion/loss of water from the bread crumb and the interactions between starch and protein macromolecules, resulting in a softer GFB crumb and reduced staling kinetics during storage. Krupa-Kozak *et al.* [2011b] reported that the addition of different levels of buckwheat flour (from 10% to 40%) improved the technological and nutritional quality of breads made with corn and potato starch. In particular, they observed that the increasing levels of buckwheat supplementation resulted in a proportional enrichment of the final products with both proteins and microelements (Cu and Mg). Turkut *et al.* [2016] demonstrated that, in gluten-free formulations based on rice flour, potato starch and buckwheat flour, the replacement of buckwheat with increasing levels of quinoa flour (up to 50%) can improve the bread sensory flavour and the overall liking, without detrimental effects on baking loss, specific volume and protein content, when levels of substitution were up to 25%.

In the last few years, apart from buckwheat flour, special emphasis has also been put on the inclusion of nutritious amaranth and quinoa flours into gluten-free formulations. Amaranth belongs to the family *Amaranthaceae* and genus *Amaranthus*, which consists of about 60 different species. Among them, *A. caudatus*, *A. cruentus*, and *A. hypochondriacus* are the three main species commonly used for food consumption. Quinoa belongs to the family *Chenopodiaceae* and genus *Chenopodium*, in which, due to the presence of bitter tasting saponins whose contents can range from 0.03 to 2.05%, it is possible to identify sweet and bitter varieties [Schoenlechner *et al.*, 2008]. Amaranth and quinoa have higher protein contents (14–15% and 13–14%, respectively) compared to the true cereal grains. Furthermore, their amino acid compositions, with high levels of the essential amino acids lysine and methionine, are well-balanced and comparable (or even higher) to those of whole egg and casein, respectively [Schoenlechner *et al.*, 2008]. In addition to protein, amaranth and quinoa are rich in many nutrients, such as dietary fibre, folate, riboflavin, ascorbic acid, tocopherol, and phenolic compounds. More-

over, they have a total mineral content (calcium, magnesium, iron, potassium, and zinc) approximately 2 times higher than that of true cereals [Schoenlechner *et al.*, 2008]. The use of both amaranth and quinoa in GFB production has been recently investigated by Machado Alencar *et al.* [2015]. These authors reported that the supplementation of a starch-rich base formulation, containing cassava, potato, sour tapioca, and rice flour with amaranth, quinoa (20%) and different sweeteners (stevia, sucralose, and sucralose/acesulfame-K blend) led to breads with higher contents of protein, lipids and ash, without detrimental effects on the specific volume, firmness, and water activity. In particular, the best results were obtained in the experimental sample prepared with quinoa and stevia, which showed the highest specific volume and the lowest crumb firmness values.

### Minor cereals: Sorghum and Teff

Sorghum (*Sorghum vulgare*) is a member of the grass family, which is more closely related to corn and wild rice than to wheat, rye and barley. For this reason, it is often used as a safe ingredient in gluten-free breadmaking [Schober *et al.*, 2007; Vallons *et al.*, 2010; Marston *et al.*, 2016]. In addition, the white and bland-taste flours obtained from the so-called food-grade sorghum lines, do not impart unusual colours or strong flavours to food products and, therefore, may be preferred over maize flour [Taylor *et al.*, 2006]. The major constituent of sorghum is starch, which constitutes about 72% of the whole grain. However, although sorghum has a similar chemical composition to that of maize, its starch tends to have a slow digesting profile and a higher gelatinization temperature, which could lead to an inadequate gelatinization during baking. Its protein content, ranging between 8.6% and 15.6%, is similar to that found in other cereal grains. Furthermore, sorghum proteins have poor nutritional quality (low lysine content) as well as poor functionality during processing. In fact, the prolamins of sorghum are located in protein bodies that have a relatively hydrophobic surface [Awika, 2017]. However, due to the large amount of bioactive compounds present in sorghum grain, it can be considered as a potential source of nutraceuticals [Taylor *et al.*, 2006]. In particular, sorghum contains phenolic acids and flavonoids, which are responsible for the different colour of sorghum grains. However, certain cultivars have higher contents of condensed tannins (proanthocyanidins) and, therefore, exhibit bitter taste [Awika, 2017]. Thus, the use of sorghum as the main ingredient in gluten-free breadmaking can have advantages but also limitations. Specifically, some physicochemical properties of sorghum flour negatively affect the breadmaking performance. In fact, during milling, the horny part of the endosperm forms coarse grits, which contribute to a coarse and sandy mouthfeel. The further milling of such grits into fine flour results in a high amount of damaged starch. Furthermore, when heated, sorghum proteins can form aggregates that, interfering with the starch gel, lead to breads with flat top and big holes in the crumb [Onyango *et al.*, 2011b]. As reported by Schober *et al.* [2005], the use of different varieties of sorghum can also affect the quality characteristics of the resulting breads. When comparing the breadmaking performance of 10 sorghum flours (70%) blended with 30%

corn starch, these authors observed significant differences in crumb hardness and crumb grain properties. They suggested that starch damage, which is influenced by kernel hardness, might have a key role in these differences. Moreover, despite no significant differences in the specific volume of the different breads, these authors concluded that larger bread volumes could be reached when corn starch is added to the sorghum flour. The importance of starch damage as well as sorghum flour composition and particles size on bread performance was also observed by Trappey *et al.* [2015]. In particular, they found that flour with a lower content of fibre and a smaller particle size enabled producing breads with more acceptable volume, crumb structure, colour, and texture. In their attempts to improve the quality of sorghum GFB, other authors adopted various promising approaches, including: (a) high-pressure processing [Vallons *et al.*, 2010] and heat treatment of sorghum flour [Marston *et al.*, 2016]; (b) the use of native and pregelatinised starch, and enzymes [Onyango *et al.*, 2010; 2011a, b]; and (c) the use of sourdough fermentation [Schober *et al.*, 2007].

Teff is an ancient cereal originating from Ethiopia where it is used to make traditional food preparations that range from typical baked goods, such as *injera* (leavened flatbread) and *kitta* (unleavened bread) through typical local spirits and opaque beer, such as *tella*, to porridge and soups [Bultosa & Taylor, 2002; Zhu, 2018]. Teff belongs to the family *Poaceae* and genus *Eragrostis*, which consists of over 350 species, of which *Eragrostis tef* is the only cultivated species. The renewed interest in the use of teff flour as a valuable ingredient in food processing is mainly due to its desirable nutritional properties and the absence of gluten. In terms of chemical composition, 73% of the total carbohydrates is composed of starch, which shows a low degree of retrogradation [Bultosa & Taylor, 2002]. The protein content of teff (8.7–11%) is close to that found in other cereals, such as wheat, maize, and barley but, unlike them, it has a well-balanced amino acid composition. Moreover, the essential amino acid profile of teff, except for its relatively lower lysine and isoleucine contents, is comparable to that of egg protein [Gebremariam *et al.*, 2014]. Since teff flour is usually obtained by grinding the whole tiny seeds, it has a high content of dietary fibre (9.8% dry basis) [Zhu, 2018]. Teff contains also considerable levels of vitamins and, compared to other cereals such as wheat, barley and sorghum, it is a good source of iron, calcium, and zinc. Furthermore, in addition to a lower lipid content (2–3%) [Schober *et al.*, 2007], teff flour is rich in unsaturated fatty acids (72.46%), including oleic acid (32.41%) and linoleic acid (23.83%) [Gebremariam *et al.*, 2014]. Although there has been a lot of research dealing with the physical, sensory, and nutritional performance of wheat breads supplemented with teff flours, only few studies have been published regarding its potential use as novel and nutritional ingredient in gluten-free breadmaking [Campo *et al.*, 2016; Marti *et al.*, 2017].

### Dietary fibre

GFB is often characterised by a low content of dietary fibre, ranging from 1.2% to 7.2% in commercial GFBs [Thompson *et al.*, 2005; Segura & Rosell, 2011]. The refining process results in a decrease in fibre content as during this process

the outer layer of grains containing most of the fibre is removed, and the starchy inner part is left. Dietary fibres consist of non-digestible carbohydrates and lignin that are intrinsic and intact in plants and should be resistant to the enzymes of the early-sections of the digestive tract and fermented in the colon by gut microbiota [Anderson *et al.*, 2009]. The daily intake of dietary fibre should range from 25 to 38 g [Drabińska *et al.*, 2018a]. The Joint WHO/FAO Expert Consultation on Diet, Nutrition and the Prevention of Chronic Diseases [Nishida *et al.*, 2004] stated that an adequate amount of fibre in the diet confers several health benefits including body mass management, as well as reduction of hypertension and risk of type 2 diabetes and cardiovascular diseases [Anderson *et al.*, 2009].

Inulin-type fructans (ITF) are commonly consumed soluble dietary fibres, which are more fermentable and viscous than the insoluble fibres [Slavin, 2013]. The structure of ITF, characterized by  $\beta$ -configuration, determines their ability to reach the colon in the intact form and their prebiotic properties [Drabińska *et al.*, 2018a]. ITF have not only nutritional quality, but can also affect the technological parameters of food products, which was widely studied in gluten-free breadmaking. Inulin can affect the quality of bread at every step of the production process. Hager *et al.* [2011] demonstrated that inulin influenced the moisture content of gluten-free batter. The inulin microcrystals led to the formation of a gel structure entrapping large volumes of water, which resulted in a less elastic and more viscous dough with a creamy texture. After baking, inulin-enriched GFB had a darker crust, but also harder crumb, and an increased rate of staling in comparison with the control bread without inulin [Slavin, 2013]. Similar findings were reported by Rodriguez *et al.* [2015], who analysed the addition of inulin to GFB fortified with bovine plasma proteins. Inulin-enriched GFB had smoother crust, increased loaf volume and reduced hardness, because of a decreased thickness of the walls surrounding the small air cells. The authors showed that inulin reduced the moisture loss and, simultaneously, delayed the staling of breads [Hager *et al.*, 2011], which in another study was found the reason behind the faster aging and staling of stored bread [Capriles & Arêas, 2013]. Korus *et al.* [2006] found that 5% enrichment of GFB with inulin resulted in an increased volume and decreased crumb hardness. However, the authors reported that too high addition of inulin may result in GFB with wrinkling crust and reduced cohesiveness and springiness of the crumb [Korus *et al.*, 2006].

ITF is a group of compounds varying in the length of the chemical chain, *i.e.* in the degree of their polymerization (DP), and consequently having different properties. Long-chain inulin significantly affects rheological and viscoelastic properties of gluten-free dough, causing a decrease in consistency and paste viscosity and an increase in the compliance values and gelatinization temperatures [Juszczak *et al.*, 2012]. On the other hand, short-chain inulin was found to increase bread volume, improve crumb texture (uniform and medium size porosity), and decrease the staling rate [Ziobro *et al.*, 2013b]. To obtain breads with various properties, a mixture of short- and long-chain ITF was also examined. Capriles & Arêas [2013] found that irrespectively of the amount of mixed

TABLE 2. By-products used in gluten-free breadmaking.

By products	Effect on gluten-free dough	Effect on gluten-free bread	References
Blackcurrant seeds	At the highest level (15%): Modified viscoelastic properties, Decreased values of consistency coefficients and flow indices	Decreases loaf volume, Slight increase in crumb hardness, gumminess and chewiness, Increased levels of proteins, dietary fibre, and polyphenols	[Korus et al., 2012]
Strawberry seeds	At the highest level (15%): Modified viscoelastic properties, Decreased values of consistency coefficients and flow indices	Increased loaf volume, Decreased crumb hardness, gumminess and chewiness, Increased levels of proteins, dietary fibre, and polyphenols	[Korus et al., 2012]
Orange pomace	Increased robustness of the batter, Decreased occurrence of starch gelatinization	Increased specific volume, Detrimental effect on crumb structure (dense and compact loaf), Decreased crumb hardness during storage (at lower level of addition), Increased levels of dietary fibre	[O'Shea et al., 2013]

fructans added, the obtained breads were characterised by an enlarged volume and specific volume, probably due to the increased CO<sub>2</sub> retention capacity. Moreover, ITFs positively affected the crust colour of GFB, probably due to enhanced formation of brown nitrogenous polymers and melanoidins via Maillard reaction during baking. The authors also confirmed the improvement in the sensory quality of GFB fortified with ITFs. Irrespective of the amount of ITF added, the enriched breads received higher scores in terms of their appearance, colour, texture, and taste. Moreover, the fortified breads had a lower glycaemic index and glycaemic load and higher contents of dietary fibre [Capriles & Arêas, 2013]. The sensory acceptance was also found to be dependent on DP [Morais et al., 2014]. GFB fortified with short-chain fructooligosaccharides received the highest scores for crust colour, porosity, and texture as well as for taste and flavour.

### By-products

Recently, about one third of the fruit and vegetable, including peels, skins, outer leaves and seeds, is wasted during preparation and processing, which poses a huge problem for both the environment and the food industry. However, many of these by-products can be used as additives to gluten-free food products, thus finding a second life (Table 2). Fruit and vegetable by-products were found to be good sources of bioactive compounds, such as carotenoids, polyphenols, glucosinolates and vitamins, as well as dietary fibre [Domínguez-Perles et al., 2010; O'Shea et al., 2012; Radočaj et al., 2014; Majzoobi et al., 2016; Drabińska et al., 2018b]. For that reason, nowadays, an increasing number of research focuses on the evaluation of the nutritional quality and further application of by- and waste products as low-cost sources of nutrients and functional ingredients.

Defatted strawberry and blackcurrant seeds have been used as additional sources of dietary fibre, protein, and polyphenols in GFB [Korus et al., 2012]. The authors found that the addition of fruit seed modified the viscoelastic properties of gluten-free batter and decreased values of consistency coefficients and flow indices. Moreover, hardness of GFB was reduced by the addition of fruit by-products, especially strawberry seeds. The incorporation of defatted strawberry seed

increased the loaf volume as compared to GFB enriched with blackcurrant seed and control bread, which was explained by a higher content of sugars which enhance the ability of yeast to produce CO<sub>2</sub> [Korus et al., 2012].

Orange pomace, being a good source of dietary fibre (up to 40% DM) and bioactive compounds (minerals, vitamins), is another by-product that has been studied in GFB development [O'Shea et al., 2013, 2015a,b; Talens et al., 2017]. The incorporation of orange pomace into gluten-free batter improved the robustness and decreased starch gelatinisation [O'Shea et al., 2013]. Furthermore, the obtained GFB enriched in orange pomace had a higher content of fibre (by 4%) [O'Shea et al., 2015b]. In turn, Talens et al. [2017] showed that an attractive colour, flavour and texture of gluten-free muffins were obtained by the incorporation of a microwave-dried orange by-product to the batter.

The recent and on-going studies demonstrated that the use of by-products in the gluten-free food industry affords the possibility of improving the quality of many products. By-products are unused sources of dietary fibre, vitamins, minerals, and bioactive compounds, which can be used to increase the quality of gluten-free foodstuff which is usually poor. However, during the optimization of a novel gluten-free product, the pre-processing step should be considered as well.

### CONCLUSIONS

The presence of gluten is considered fundamental for successful breadmaking. However, the elimination of gluten in cereal-based products has a detrimental effect on the breadmaking process and raises technological challenges in making good quality leavened bread. On the basis of the recent findings summarized in this review, it may be concluded that only the use of a combination of different ingredients and additives could result in GFBs with pleasant quality features that, in some cases, may be compared to those of the gluten-containing breads. In particular, the partial replacement of the conventional starchy ingredients with alternative nutrient-dense minor cereals, pseudocereals, and legumes allowed achieving promising results. The incorporation of low-cost sources of nutrients, such as different kinds of by- and waste

products, has also been suggested as an interesting approach to improve the quality of GFB.

However, despite the considerable advances made in this field, the nutritional quality of gluten-free products still remains a critical issue. Since low levels of protein, fibre, and essential nutrients, as well as high contents of fat and sugar are too often observed in GFB, further research aimed at exploring new strategies to overcome this major problem is needed.

### CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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