

Invited Review

Gluten-free bakery and pasta products: prevalence and quality improvementYupeng Gao,¹ Marlene E. Janes,¹ Busarawan Chaiya,² Margaret A. Brennan,³ Charles S. Brennan³ & Witoon Prinyawiwatkul^{1*} 

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Summary An increasing demand of gluten-free (GF) products is caused by a growing number of diagnosed coeliacs and a consumption trend to eliminate allergenic proteins from diet. Driven by the rapidly growing market, comprehensive understanding of GF products is necessary. The purpose of this review was to concisely present an overview of various approaches to improve physicochemical and sensory qualities of GF bread, cake/muffin and pasta/noodle products. Some novel techniques used in GF products were discussed in this review. These techniques included the use of different alternative flours (including GF cereals, pseudo-cereals, legume flours, fruit and vegetable powders and seafood powders), functional ingredients (including hydrocolloids and gums, emulsifiers, proteins and dietary fibres) and optimal processing (pretreated flour, infrared–microwave combination baking and extrusion cooking). Some recent novel technologies including transgenesis, enzymolysis and fermentation that have been used on GF products were also discussed.

Keywords Baked products, coeliac disease, gluten, gluten-free, pasta, wheat.

Introduction

Gluten includes a mixture of over one hundred proteins prevalent in grains, for example, wheat, rye, spelt and barley (Wieser, 1996). For people born with certain health conditions, and as humans age, the gluten in wheat can cause problems (Armstrong *et al.*, 2012; Aronsson *et al.*, 2015; Fritz & Chen, 2017). There are three main forms that human reacts towards gluten intake: allergic (wheat allergy), autoimmune (coeliac disease, dermatitis herpetiformis and gluten ataxia) and immune-mediated (gluten sensitivity) (Sapone *et al.*, 2012). Coeliac Disease (CD) is a chronic small intestinal immune-mediated enteropathy precipitated by exposure to dietary gluten in genetically predisposed individuals (Ludvigsson *et al.*, 2012). There are a set of diverse clinical features, which includes fatigue, weight loss, diarrhoea, anaemia, osteoporosis and depression (Rashtak & Murray, 2012; Gélinas & McKinnon, 2016). A strict gluten-free (GF) diet is the only available therapeutic treatment for consumers

with CD. However, besides the CD consumers, some consumers avoid gluten as part of their lifestyle. Despite the proven benefits and an increasing trend of GF diet, it can be very difficult to completely avoid gluten-containing foods, and adherence to GF diet is estimated to be only 45–80% (Nadhem *et al.*, 2015).

Currently processed and prepackaged foods including baked goods, pastas and breakfast cereals are widely produced using gluten-containing raw materials, especially from wheat (Zarkadas *et al.*, 2013; Gélinas & McKinnon, 2016). According to the definition of GF by Codex Alimentarius, only foods made from naturally GF ingredients which could contain no more than 20 parts per million (ppm) gluten can be called GF products (Codex Alimentarius Commission, 2007). Therefore, GF products usually have a poor texture and weak flavour that are caused by the lack of gluten protein (Saturni *et al.*, 2010).

In recent years, there has been an increasing interest on GF food products. The market for GF products is projected to grow at a compound annual growth (CAGR) rate of 10.4% from \$4.63 billion in 2015 to reach \$7.59 billion in 2020 (Marketsandmarkets,

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2015). The percentage of GF food and beverage launch activity during 2013–2015 increased from 7.9% to 11.8% (Williams, 2015). A survey (The Gluten-Free Agency, 2012) reported that consumers in the 25–34 and 50–64 age ranges in North America are more likely to be influenced by GF marketing and claims. Males are more influenced by GF marketing and claims than females in North and South America. In 2014, the global GF product market was led by North America, where the U.S. consumers are an important segment both in terms of volume and values. In terms of values, Europe is projected to be the fastest growing market (Marketsandmarkets, 2015).

The production of traditional bakery products involves four steps: ingredient mixing, dough kneading, fermentation and baking. Gluten plays an important role in all of these procedures (Zhou *et al.*, 2014). As a result, GF bakery products are often less desirable in terms of their appearance, taste, aroma and texture. The simplest way to improve the structure of GF products is by adding other functional ingredients and additives (e.g. starches, protein, gum, hydrocolloids, emulsifiers, dietary fibre) to the wheat flour substitutes (e.g. rice, maize, sorghum, buckwheat, amaranth, quinoa, corn, chickpea) as reported by numerous authors (Arendt & Moore, 2006; Janković *et al.*, 2015; Rocha Parra *et al.*, 2015; Akesowan, 2016). Extensive review on GF bread-making, including compositions of the standard recipes as well as the GF recipes consisting of flour or starch from various sources and additives, was provided by Masure *et al.* (2016).

The production of traditional pasta and noodle products is simple and convenient. The primary factor in assessment of pasta and noodle quality is the texture properties, which also directly influence consumer acceptance. Desirable pasta and noodle should exhibit high firmness, absence of stickiness and low cooking loss, which can be attributed to the specific structural organisation of starch and proteins (Marti *et al.*, 2014a,b). The lack of gluten affects the structure of the matrix by reducing the continuous network formed by coagulated gluten proteins (Padalino *et al.*, 2016). The improvement of GF pasta and noodle has been focused on selection of materials (pseudo-cereals, legume flours and vegetable or fruits powder) and modified processing methods (Marcella *et al.*, 2012; Giuberti *et al.*, 2015; Sarawong *et al.*, 2014; Rafiq *et al.*, 2017). According to Padalino *et al.* (2016), GF technology primarily depends on dough heating and cooling operations, before starch gelatinisation and its subsequently retrogradation. These authors further detailed technological options for improving GF pasta and bread.

The purpose of this review was to concisely summarise current progress in development of GF

products, focused particularly on bakery (bread, cake, and muffin), and pasta and noodle products. Various alternative flours (GF cereals, pseudo-cereals, legume flours, fruit and vegetable powders and seafood powders), functional additives (hydrocolloids and gums, emulsifiers, proteins and dietary fibres) and optimal processing (pretreated flour, infrared-microwave combination baking and extrusion cooking) for GF bakery, pasta and noodles were discussed. Some recent novel technologies including sourdough technology, transgenesis, enzymolysis and fermentation (Turabi *et al.*, 2010; Badiu *et al.*, 2014) that have been applied to GF products were also discussed in this review.

GF breads

Substitute flours and starches

Table 1 lists the composition of GF bread formulas, including flour or starch sources, additives and new technologies. Bread formulas based on rice, buckwheat, sorghum, quinoa, oat, maize, teff and chia flours are commonly used. These flours are rich in protein, minerals and fibre (Alvarez-Jubete *et al.*, 2010; Mezaize *et al.*, 2010). Rice flour is widely used in Western countries for its neutral flavour and pale colour, making it simpler to incorporate in many products. Additionally, rice protein is also hypoallergenic. Usually rice flour is combined with other flours such as oat, amaranth, tigernut, chestnut and chickpea. Starch sources as a sole substitute for wheat flour are rarely used. In formulas with a combination of different flours and starches, rice flour has been often combined with potato, corn and cassava starch. Buckwheat flour and flours from legumes such as pea, chickpea, chestnut and carob were also used in combination with different starches (Table 1). In Table 1, based on the rice flour and corn starch, GF flour formulas were used to explore the influence of different additives (Demirkesen *et al.*, 2010; Ziobro *et al.*, 2013; Martínez *et al.*, 2014).

Functional additives

Several types of additives are widely used in GF breads (Table 1). Hydrocolloids were used to improve texture of GF breads. The most common hydrocolloid is hydroxypropyl methylcellulose (HPMC), followed with carboxymethylcellulose (CMC) and methylcellulose (MC). The addition of hydrocolloid offers a strategic role in making the GF dough workable and improving the texture of the final GF product. Other commonly used hydrocolloids are xanthan gum, guar gum and locust bean gum. Demirkesen *et al.* (2014) used X-ray microtomography to show that a cohesive crumb was observed in breads prepared with xanthan-guar, xanthan-locus bean gum, HPMC and CMC. Addition of proteins significantly modified colour and textural properties of bread crumb. Albumin, collagen,

Table 1 Substitute flours and alternative functional additives and technology applied to gluten-free breads

Substitute Flour	Additives & Technology	References
Rice flour; teff flour; maize flour; buckwheat flour	HPMC, xanthan gum	Hager & Arendt (2013)
Starch	Whey protein, structured protein suspension	van Riemsdijk <i>et al.</i> (2011b)
Rice flour, tigernut flour	DATEM, xanthan gum, guar gum; Infrared–microwave combination heating	Demirkesen <i>et al.</i> (2013a)
Rice flour, carob flour, resistant starch	DATEM, Locust bean gum, whey protein concentrate, α -amylase, transglutaminase, hemicellulase	Tsatsaragkou <i>et al.</i> (2014)
Rice flour, quinoa flour	Xanthan gum	Alvarez-Jubete <i>et al.</i> (2010)
Rice flour, potato starch, potato flour, flaxseed flour	DATEM, xanthan gum, guar gum, locust bean gum; Infrared–microwave combination heating	Ozkoc & Seyhun (2015)
Rice flour, potato starch, cassava starch, sour tapioca flour	Egg, fructose, inulin, sucralose	de Morais <i>et al.</i> (2013)
Rice flour, corn starch, chestnut flour	HPMC, lupine protein, vegetable fibre; Guar gum, skimmed milk, cellulose	Paciulli <i>et al.</i> (2016)
Rice flour, corn starch	Pectin, skim milk, whole egg powder, soy protein, xanthan gum	Matos & Rosell (2013)
Rice flour, corn flour, rice starch, rice protein	HPMC, locust bean gum, guar gum, psyllium fibre, sugar beet fibre; Maltogenic amylase	Cappa <i>et al.</i> (2013)
Rice flour, corn starch	HPMC, bamboo fibre, oat fibre, pea fibre, potato fibre	Martínez <i>et al.</i> (2014)
Rice flour, corn flour, corn starch, quinoa white flour	HPMC, amyloglucosidase, α -amylase; Sourdough fermentation	Elgeti <i>et al.</i> (2014)
Rice flour, chestnut flour	DATEM, xanthan gum	Demirkesen <i>et al.</i> (2014, 2013b)
Rice flour, buckwheat flour, chickpea flour	Green mussel protein hydrolysates	Vijaykrishnaraj <i>et al.</i> (2016)
Rice flour, buckwheat flour	Xanthan gum	Torbica <i>et al.</i> (2010)
Rice flour, barley flour, oat flour	HPMC	Ronda <i>et al.</i> (2015)
Rice flour	DATEM, agar, CMC, MC, xanthan gum, guar gum, locust bean gum	Demirkesen <i>et al.</i> (2010)
Rice flour	HPMC	Matos & Rosell (2013)
Rice flour	HPMC, β -glucan	Ronda <i>et al.</i> (2013)
Rice flour	HPMC, β -glucan, whey protein	Kittisuban <i>et al.</i> (2014)
Rice flour	Proteases, thermolysin	Kawamura-Konishi <i>et al.</i> (2013)
Rice flour	Soy milk, albumin	Nozawa <i>et al.</i> (2016)
Rice flour	Transglutaminase, albumin, casein	Storck <i>et al.</i> (2013)
Reduced-gliadin wheat flour	Transgenic	Gil-Humanes <i>et al.</i> (2014a)
Quinoa flour	<i>L. amylovorus DSM 19280</i> , <i>L. amylovorus DSM 20531</i> ; Sourdough fermentation	Axel <i>et al.</i> (2015)
Quinoa flour	Lactic acid bacteria, <i>Lactobacillus plantarum T6B10</i> , <i>Lactobacillus rossiae T0A16</i> ; Sourdough fermentation	Rizzello <i>et al.</i> (2016)
Oat flour	<i>Lactobacillus plantarum FST 1.7</i> ; Sourdough fermentation	Wolter <i>et al.</i> (2014b)
Maize flour	HPMC	de la Hera <i>et al.</i> (2013)
Jasmine Rice, pregelatinised tapioca starch	Transglutaminase	Pongjaruvat <i>et al.</i> (2014)
Corn starch, potato starch, buckwheat flour	Pectin	Wronkowska <i>et al.</i> (2013)
Corn starch, potato starch	Pectin, albumin, collagen, lupine protein, pea protein isolate, soy protein	Ziobro <i>et al.</i> (2013)
Corn starch, potato starch	Pectin, whey protein	Krupa-Kozak <i>et al.</i> (2013)
Corn starch, pea isolate, chickpea flour, carob germ flour, soya flour	DATEM, xanthan gum	Miñarro <i>et al.</i> (2012)
Corn starch, amaranth flour	Pea isolate, psyllium fibre	Mariotti <i>et al.</i> (2009)
Chestnut flour, chia flour	HPMC, guar gum; tragacanth gum	Moreira <i>et al.</i> (2013)
Buckwheat flour, quinoa flour, sorghum flour, teff flour	<i>W.cibaria MG1</i> , exopolysaccharide; Sourdough fermentation	Wolter <i>et al.</i> (2014a)
Buckwheat flour, chia flour	Sourdough fermentation	Costantini <i>et al.</i> (2014)

soy protein, whey protein, lupine protein and egg powder have been used as protein sources in GF breads. Ziobro *et al.* (2013) used nongluten protein supplement in bread-making. They reported that soy protein and collagen reduced specific loaf volume of

bread, while lupine and albumin resulted in a significant increase. Fibre from psyllium, sugar beet, oat, pea and bamboo can improve texture, gelling, thickening and stabilising properties to GF bread. Emulsifiers can interact and form complexes with starch, protein,

shortening and water, hence lowering the surface tension of dough. The interaction of emulsifiers and hydrocolloids could lead to a subdivision of the air bubbles inside the dough (Mert *et al.*, 2016). Therefore, the pores of GF breads were found to be smaller and more uniform in size, which helped improve the texture of GF breads.

GF cake & muffin products

Substitute flours and starches

It has been reported that particle size of flours is one of the most important factors affecting cake characteristics, and gluten may not play an important role in cake products (Gómez *et al.*, 2010, 2012). As such, flours from other cereals or legumes can be used (O'Shea *et al.*, 2014) but they likely modify sensory properties, particularly flavour and texture of GF cake and muffin products. Rice flour was widely used to replace wheat flour in GF cake and muffin (Table 2). Rice flour with particle size smaller than 100 µm increased dough viscosity

(compared to coarser rice flour) and created small uniform bubbles in cake (de la Hera *et al.*, 2013; Kang *et al.*, 2015); 100% rice flour and a replacement of quinoa flour up to 75% to rice flour could be used to produce acceptable GF muffins (Bhaduri, 2013); 100% rice flour muffin was softer with a significantly higher acceptability score than 100% wheat flour muffin. Likewise, HI-MAIZE® resistant and tapioca starches (Tsatsaragkou *et al.*, 2015) and potato starch (Yildiz & Dogan, 2014) can be used to decrease the batter density (less elastic and thinner), hence increasing the volume and uniform pore of rice cake. Extruded broken bean flour from chickpea, kidney bean and lentil were used for GF cake blends (Gomes *et al.*, 2015). Legumes may also affect the *in vitro* hydrolysis of starch fractions, decreasing the rapidly digestible starch yielding (Gularte *et al.*, 2012a). Other GF flours from chai, sorghum, quinoa and teff were also used in GF cakes and muffin (Bhaduri & Navder, 2014; Marston *et al.*, 2014; Rothschild *et al.*, 2015; Tess *et al.*, 2015; Gohara *et al.*, 2016).

Table 2 Substitute flours, and alternative functional additives and technology applied to gluten-free cake & muffin products

Substitute Flour	Additives & Technology	References
Chestnut flour, potato starch	Transglutaminase, emulsifier, shortening, xanthan gum, guar gum	Tambunan <i>et al.</i> (2015)
Partially defatted baru flour	Xanthan gum, margarine	de Oliveira Pineli <i>et al.</i> (2015)
Potato starch, sorghum flour	Emulsified shortening, dextrose	Marston <i>et al.</i> (2016)
Quinoa flour, nava bean flour	Whole-grain milk (brown rice, amaranth and millet), apple cider vinegar, agave syrup, maple syrup	Rothschild <i>et al.</i> (2015)
Rice flour	Inulin, guar gum, oat fibre, pancreatin, amyloglucosidase, oxidase-peroxidase	Gularte <i>et al.</i> (2012a)
Rice flour	Invert syrup, tragacanth, xanthan gum	Hojjatoleslami & Azizi (2015)
Rice flour		Jeong <i>et al.</i> (2013)
Rice flour	Emulsifier	de la Hera <i>et al.</i> (2013)
Rice flour	Xanthan gum, guar gum, locust bean gum; Infrared-microwave combination heating	Turabi <i>et al.</i> (2010)
Rice flour, azuki flour, chia flour		Gohara <i>et al.</i> (2016)
Rice flour, corn flour	Carrot pomace powder, lecithin	Majzoubi <i>et al.</i> (2016)
Rice flour, corn starch, kidney beans	Broken bean flour technological	Gomes <i>et al.</i> (2015)
Rice flour, legume flour, chickpea flour, pea flour, lentil flour, bean flour	α -amylase, amyloglucosidase, trypsin, glucose oxidase-peroxidase	Gularte <i>et al.</i> (2012b)
Rice flour, resistant starch, tapioca starch	Locust bean gum, DATEM	Tsatsaragkou <i>et al.</i> (2015)
Sorghum flour	Dextrose, emulsified shortening; ozone	Marston <i>et al.</i> (2014)
Water chestnut flour	Carboxymethyl cellulose, sodium alginate, guar gum	Mir <i>et al.</i> (2015)
Chickpea flour	Whey protein, xanthan gum, inulin	Herranz <i>et al.</i> (2016)
Corn flour	Egg yolk granules, apple pectins, gelatin	Marcet <i>et al.</i> (2015)
Corn starch	Kidney bean flour, field pea flour, amaranth protein isolates	Shevkani & Singh (2014)
Rice flour	Soya protein isolates, glycerol monostearate, xanthan gum, black carrot dietary fibre concentrate	Singh <i>et al.</i> (2016)
Rice flour	Soya bean protein isolate, pea protein isolate, egg white protein, casein, xanthan gum	Matos <i>et al.</i> (2014)
Rice flour	Jambolan fruit pulp, soy protein isolate, glycerol monostearate, xanthan gum	Singh <i>et al.</i> (2015)
Rice flour, cowpea flour		Shevkani <i>et al.</i> (2015)
Rice flour, quinoa flour	Freeze-dried blueberry powder	Bhaduri & Navder (2014)

Functional additives

Hydrocolloids, protein, emulsifier and fibre are the main additives in GF cakes and muffins (Table 2). Mir *et al.* (2015) used water chestnut flour with CMC (1%) to control moisture content and texture of GF cakes, while xanthan gum and xanthan–guar blend were used to increase the crumb porosity of GF eggless rice muffins (Singh *et al.*, 2015) and GF rice cakes (Turabi *et al.*, 2010). Hojjatoleslami & Azizi (2015) illustrated that a combination of tragacanth (0.5%) and xanthan (1%) gums in GF cakes reduced texture stiffness and maximised moisture content. Herranz *et al.* (2016) used xanthan gum to produce a chickpea flour-based GF muffin with similar hardness to wheat gluten muffins.

Addition of protein from egg was performed to improve the structure of GF cakes (O'Shea *et al.*, 2014; Marcet *et al.*, 2015) and rheological properties, particularly the viscoelastic behaviour of batter of rice-based GF muffins (Matos *et al.*, 2014). However, to produce a GF and egg-free cake, Tambunan *et al.* (2015) used soy isolate protein along with corn starch and guar gum to improve the texture and appearance of GF cakes. Shevkani & Singh (2014) used protein isolates from kidney bean, field pea and amaranth to improve gas cell formation and the springiness of GF muffins.

Nonstarch polysaccharides often create harder textures in GF products compared to non-GF foods, even though addition of fibres can increase the slowly digestible starch content (Gularte *et al.*, 2012b). Muffin containing black carrot pomace dietary fibre concentrate had an increased total dietary fibre content, decreased L^* and b^* values and decreased water activity (Singh *et al.*, 2016). When carrot pomace powder (CPP) was used as a fibre additive in a rice- and corn-based GF cake product, texture hardness increased compared to the control (Majzoobi *et al.*, 2016) (Fig. 1).

GF pasta and noodle products

Pasta is very popular and consumed worldwide due to its long shelf life, ease of storage and simple meal preparation (Sobota *et al.*, 2015). High-quality pasta usually is characterised by desirable cooking resistance and firmness, low stickiness and limited cooking loss (Lucisano *et al.*, 2012). Protein and starch in pasta have a completely different behaviour during cooking. The starch granules swell and partly solubilise during cooking, while the protein becomes insoluble and coagulate (Hager *et al.*, 2012). Gluten plays a key role in protein coagulation and influences the texture of cooked pasta. Therefore, choosing suitable raw material and modifying processing condition for producing GF pasta are two important ways to improve GF pasta eating quality.

Substitute flours and starches

Various wheat flour substitutes have been used for GF pasta and noodle production (Table 3), including pseudo-cereals, legume flours and vegetable or fruits powders. However, the more popular raw materials are rice and corn. Pastas are usually extruded while Asian noodles are sheeted. In fact, Asian rice noodle and most starch-based noodles are commonly GF products. Utilisation of rice in GF pasta and noodle formulations has been well documented in the literature (Marti *et al.*, 2010; da Silva *et al.*, 2013; Cai *et al.*, 2016; Rafiq *et al.*, 2017). Curiel *et al.* (2014) prepared wheat flour (GFWF), which was rendered gluten free by sourdough lactic acid bacteria fermentation and fungal proteases. They reported that in the absence of gluten network, supplementing pregelatinised rice flour could provide structural properties of GFWF pasta comparable to that of the durum wheat pasta. Amylose and/or amylopectin in rice pasta play a key role in creating a starch network, accounting for the texture integrity of pasta after cooking (Marti *et al.*, 2010). Cooking of rice starch leads to gelatinisation which occurs at the same time as protein denaturation (Cabrera-Chávez *et al.*, 2012). Through heating and cooling stages, pregelatinised starch forms a rigid network (Foschia *et al.*, 2017). Furthermore, the combination of starch gelatinisation and protein denaturation builds a compact structure to increase the firmness of GF pasta. da Silva *et al.* (2016) prepared GF pasta with brown rice (BR) and corn meal (CM) blends and reported that the pasta produced with a 40:60 (CM:BR) blend received better texture (sensory and instrumental).

Kahlon *et al.* (2013) developed whole grain, high protein, GF, egg-free pasta from corn, millet, brown rice sorghum flours and whole garbanzo flour (to increase the protein content). Sensory acceptance for brown rice–garbanzo and corn–garbanzo pasta was similar and significantly higher than millet–garbanzo and sorghum–garbanzo pasta. A mixture of corn starch, corn flour and rice flour was reported to improve the texture and cooking ability of GF pastas (Lucisano *et al.*, 2012; da Silva *et al.*, 2016).

Buckwheat, amaranth, quinoa, teff and oat are becoming increasingly popular as ingredients in pasta formulations as they improve the nutritional quality of GF pasta. Precooked buckwheat pasta contained natural polyphenolic antioxidants and composite of gallic, protocatechuic, gentisic, 4-OH-benzoic, vanillic, trans-caffeic, cis-caffeic, trans-pcoumaric, cis-pcoumaric, trans-ferulic, cis-ferulic and salicylic (Oniszczuk, 2016). Kahlon & Chiu (2015) prepared GF egg-free pasta from different pseudo-cereals including teff, buckwheat, quinoa and amaranth. Odour of buckwheat pasta and texture/mouthfeel of teff pasta were

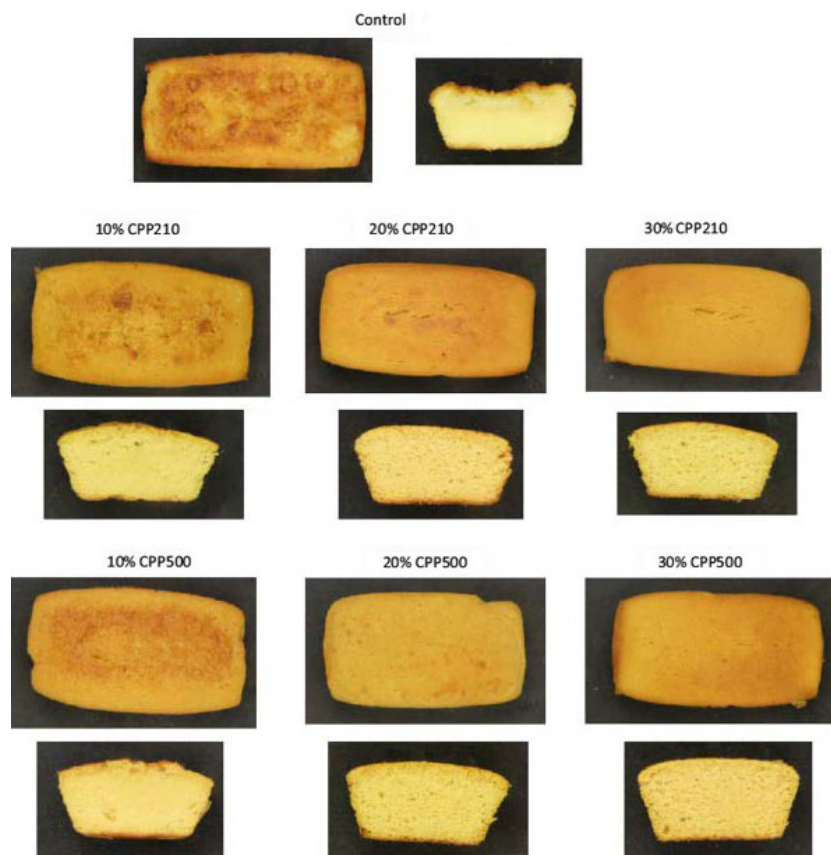


Figure 1 Surface and cross section of gluten-free cakes containing 0% (control), 10%, 20% and 30% carrot pomace powder with particle size of 210 μm (CPP 210) and 500 μm (CPP 500). Source: Majzoobi *et al.* (2016). [Colour figure can be viewed at wileyonlinelibrary.com]

significantly better than quinoa and amaranth pasta. Taste/flavour of teff and buckwheat pasta was similar and significantly better than quinoa and amaranth pasta (Kahlon & Chiu, 2015). The mechanical texture of oat and teff GF pasta was comparable to that of wheat pasta, but its elasticity was significantly reduced (Hager *et al.*, 2012). Stickiness of oat and wheat pasta was in the same range but higher than teff pasta (Hager *et al.*, 2012).

GF spaghetti made of amaranth flour with extruded potato pulp was reported to have better colour, less solid loss to cooking water and higher yield, and required less cooking time compared to fresh commercial wheat spaghetti (Bastos *et al.*, 2016). A pasta made of cassava starch, amaranth flour and pregelatinised flour required 3 min of cooking time, having mass increase of 101.5% and 0.6% solid loss to cooking water. This pasta was highly acceptable with an overall liking score of 7.2 on a 9-point scale, and obtained 42% buying intention amongst the consumers (Fiorda *et al.*, 2013a). This pasta also had a light yellowish colour, high fibre [9.37 g/100 g], high protein [10.41 g/100 g], adequate firmness (43.6 N) and low stickiness (3.2 N) (Fiorda *et al.*, 2013b).

Recently, the use of fruit and vegetable powder in GF pasta has increased. Banana flour, rich in indigestible carbohydrates, has been used to produce GF pasta (Zandonadi *et al.*, 2012; Radoi *et al.*, 2015). Adding 30% pregelatinised green plantain flour or drum-dried green banana flour produced GF spaghetti with acceptable cooking quality and high-resistance starch. Mirhosseini *et al.* (2015) used pumpkin flour or durian seed flour to produce GF pasta. The addition of 25% pumpkin flour to the formulation led to improved colour and texture properties and sensory acceptance of GF pasta.

Functional additives

Hydrocolloids are commonly added in GF pasta formulations to improve cooking as the GF pasta typically has an inferior texture and usually does not tolerate overcooking. Addition of texturing ingredients can improve firmness, increase rehydration and reduce the sticky texture of GF pasta. Larrosa *et al.* (2013) prepared GF pasta containing corn starch (42.8%) and corn flour (10.7%) with different amounts of locust bean gum (0.5–2.5%), egg proteins (0.7–6.7%) and water (35.5–39.5%). They mathematically modelled the rheological spectra of GF pasta dough and

Table 3 Substitute flours and alternative functional additives and technology applied to gluten-free pasta and noodle products

Substitute Flour	Additives & Technology	References
Wheat flour	Sourdough lactic acid bacteria, fungal proteases	Curiel <i>et al.</i> (2014)
Teff flour; buckwheat flour; quinoa flour; amaranth flour	Guar gum	Kahlon & Chiu (2015)
Teff flour, bean flour		Giuberti <i>et al.</i> (2015)
Soy flour, channa flour, sorghum flour	Whey protein concentrate, guar gum, HPMC	Susanna & Prabhasankar (2013)
Rice flour, yellow pea flour		Bouasla <i>et al.</i> (2016)
Rice flour, resistant starch	Propylene glycol alginate, monoglycerides	Foschia <i>et al.</i> (2017)
Rice flour, potato starch	Xanthan gum	da Silva <i>et al.</i> (2013)
Rice flour, green banana flour	Egg albumen powder, distilled monoglyceride	Sarawong <i>et al.</i> (2014)
Rice flour, corn starch	Milk protein, guar gum, xanthan gum, cheese	Sanguinetti <i>et al.</i> (2015)
Rice flour, corn starch	Milk protein, xanthan gum, animal fat, cheese, lemon juice	Sanguinetti <i>et al.</i> (2016)
Rice flour, banana	Egg	Radoi <i>et al.</i> (2015)
Rice flour, amaranth seed flour		Cabrera-Chávez <i>et al.</i> (2012)
Rice flour	Egg albumen, whey protein	Marti <i>et al.</i> (2014a,b)
Potato pulp, amaranth flour	Fresh egg	Bastos <i>et al.</i> (2016)
Plantain flour, chickpea flour, white corn flour	CMC	Flores-Silva <i>et al.</i> (2015)
Maize flour, artichoke flour; asparagus flour; pumpkin flour; zucchini flour; tomato flour; yellow pepper flour; red pepper flour; green pepper flour; carrot flour; broccoli flour; spinach flour; eggplant flour; fennel flour	Monoglycerides	Padalino <i>et al.</i> (2013)
Maize flour	Inulin	Marcella <i>et al.</i> (2012)
Jabuticaba peel flour, rice flour	Albumin powder	Garcia <i>et al.</i> (2016)
Green mussel powder, chickpea flour		Vijaykrishnaraj <i>et al.</i> (2015)
Green banana flour	Egg white, guar gum, xanthan gum	Zandonadi <i>et al.</i> (2012)
Glutinous rice flour, rice flour	Xanthan gum	Cai <i>et al.</i> (2016)
Corn starch, corn flour, potato starch, rice flour	Pea protein isolate, lupin flour	Lucisano <i>et al.</i> (2012)
Corn starch, corn flour	Dry egg, dry egg white, xanthan gum, locust bean gum, sunflower oil	Larrosa <i>et al.</i> (2016, 2015, 2013), Larrosa <i>et al.</i> (2012)
Corn flour, millet flour, brown rice flour, sorghum flour, garbanzo flour	Guar gum	Kahlon <i>et al.</i> (2013)
Corn flour, corn starch, pumpkin flour, durian seed flour	Dry egg powder	Mirhosseini <i>et al.</i> (2015)
Corn flour		Giménez <i>et al.</i> (2015)
Cassava starch, cassava bagasse, amaranth flour	Egg, urucu dye powder	Fiorda <i>et al.</i> (2013b)
Cassava starch, cassava bagasse, amaranth flour	Whole egg, annatto dye powder	Fiorda <i>et al.</i> (2013a)
Buckwheat flour, quinoa flour, amaranth flour	Monoglyceride, egg white powder	D'Amico <i>et al.</i> (2015)
Buckwheat		Oniszcuk (2016)
Brown rice, corn grits		da Silva <i>et al.</i> (2016)
Brown rice flour; parboiled rice flour		Marti <i>et al.</i> (2010)
Brown rice flour		Rafiq <i>et al.</i> (2017)
Amaranth flour, quinoa flour, buckwheat flour	DATeM, egg white powder; casein; soy protein isolate	Schoenlechner <i>et al.</i> (2010)
Amaranth flour, oat flour, rice flour		Sakre <i>et al.</i> (2015)

discovered that decreasing water and increasing gum content produced a more elastic polymer network. Cai *et al.* (2016) reported quality improvement of GF noodles formulated using hydrothermally treated polysaccharide mixtures (HTT-PSM) of glutinous rice flour and xanthan gum at different concentrations. They reported that HTT-PSM had high extensibility which enabled the dough to make GF noodles with higher tensile strength and similar texture profile as compared to wheat noodles. Effect of xanthan and guar gum on GF pasta was evaluated by Sanguinetti

et al. (2015). The xanthan gum pasta retains moisture during storage, hence inhibiting development of crack fractures on the dough surface, which appeared on the guar gum pasta after 7 days of storage (Sanguinetti *et al.*, 2015).

Other approaches to improve GF baked and pasta quality

Extrusion-cooking processes

Pasta products are normally produced using cold single screw extrusion process. The twin screw extruder

can be successfully applied in the production of brown rice GF pasta at elevated feed moisture and screw speed. At the optimised condition [feed moisture (31.1%), screw speed (177.9 rpm) and barrel temperature (87 °C)], the cooking loss was less than 10% indicating good quality products (Rafiq *et al.*, 2017). Starch hydration properties can be greatly affected by extrusion parameters as when starch granules are heated in the presence of water, the hydrogen bonds that hold the structure will weaken, thus allowing the granules to absorb water and swell (Marti *et al.*, 2010; Flores-Silva *et al.*, 2015). As starch is the major component of the rice kernel, changes in physicochemical properties during extrusion processes will dictate the properties of rice pasta. The extrusion-cooking process caused strong interactions of amylopectin and/or amylose. Consequently, the product had a low cooking loss but a high firmness (Marti *et al.*, 2010).

Temperature control

This is an important parameter for GF bread and cake. Infrared–microwave combination heating (Turabi *et al.*, 2010) has been used as alternative technologies to aid the production of GF products. For GF bread, some studies used infrared–microwave heating technology to improve moisture distribution inside the food and to remove the surface moisture faster, hence increasing the pore number while decreasing the pore size (Demirkesen *et al.*, 2013a,b). Lyophilisation has been used for preparing sourdough (Różyło *et al.*, 2015). The use of sourdough lyophilised at 20 °C led to the production of larger volumes in GF bread; however, the structure of crumb and shelf life was better when lyophilised temperature was at 40 °C (Fig. 2). The higher preparing temperature at 60 °C caused the least changes in bread volume.

The mathematical modelling

The mathematical modelling of the rheological spectra of GF pasta dough allowed an interpretation of the effect of water and biopolymers on viscoelastic behaviour of the dough. Larrosa *et al.* (2013) reported the optimal composition (35.5% water, 2.5% gums, 4.7% proteins, 42.8% corn starch, 10.7% corn flour, 1% NaCl and 2.8% sunflower oil) yielded the highest G' value, breaking force and extensibility based on the Baumgaertel–Schausberger–Winter model. Larrosa *et al.* (2015) evaluated effects of cooking times and dough composition (corn starch, corn flour, NaCl, dry egg and dry egg white powders, sunflower oil, xanthan and locust bean gums) on the rheological properties of GF pasta. Small-amplitude oscillatory data were used to obtain the relaxation spectrum and were satisfactorily predicted using the Maxwell Generalised model. Water uptake by the matrix, partial gelatinisation of the starch and aggregation of denatured egg proteins

were more influenced by cooking time than protein and water contents, which led to chemical and morphological changes of the cooked pasta. This same group of authors (Larrosa *et al.*, 2016) further evaluated effects of dough composition (water and egg protein content) of GF pasta on viscoelastic, textural and quality attributes of the cooked product. The elastic behaviour of GF pasta was mainly affected by dough moisture, while springiness, resilience and adhesiveness were mainly affected by the egg-protein content in the dough. The authors reported that cooked pasta hardness increased with decreased dough moisture and increased starch content. The optimal composition (6.6% egg protein and 35.96% water) was used to obtain high-quality GF cooked pasta.

Even though alternative flours and modified processes improve the texture and cooking quality of GF pasta, there are still some shortcomings of GF pasta compared to the wheat pasta. Therefore, utilising bioprocessing fermentation and transgenesis to modify wheat flour have gained more attention recently.

Bioprocessing fermentation

Bioprocessing fermentation has been applied to eliminate or reduce the gluten protein in wheat flour. According to Sollid *et al.* (2012), the nine amino acid core sequences of some restricted but unique epitopes were identified in wheat, barley and rye which stimulated a response in individuals with coeliac disease. To eliminate the gluten protein, different lactic acid bacteria, yeasts and enzymes have been used in sourdough fermentation. Picozzi *et al.* (2016) utilised a GF matrix inoculated with *Lactobacillus sanfranciscensis* and *Candida humilis*, fermented to pH 4.0 and constantly propagated for ten times to obtain a type I GF sourdough, which improved the overall quality of GF baked products. Gerez *et al.* (2012) utilised *Lactobacillus plantarum* CRL775 and *Pediococcus pentosaceus* CRL 792 to improve hydrolysis of gliadin during dough fermentation without yeasts as a starter. Giuliani *et al.* (2012) utilised a mixture of *Lactobacillus sanfranciscensis* DSM22063 and *Lactobacillus plantarum* DSM 22064 as well as fungal proteolytic enzymes from *Aspergillus oryzae* or *Aspergillus niger* to get a complete degradation of gluten protein. In another study, *Lactobacillus sanfranciscensis*, *Lactobacillus alimentarius*, *Lactobacillus brevis* and *Lactobacillus hilgardii* and fungal proteases from *Aspergillus oryzae* and *Aspergillus niger* were used to eliminate gluten in wheat flour (below 10 ppm), which was then used to prepare GF pasta. This GF pasta exhibited rapid water uptake and shorter optimal cooking time, and its essential amino acid profile, biological value and nutritional index were higher than durum wheat paste (Curiel *et al.*, 2014). *Lactobacillus amylovorus* and other lactic acid bacteria (LAB) have also been used to improve texture

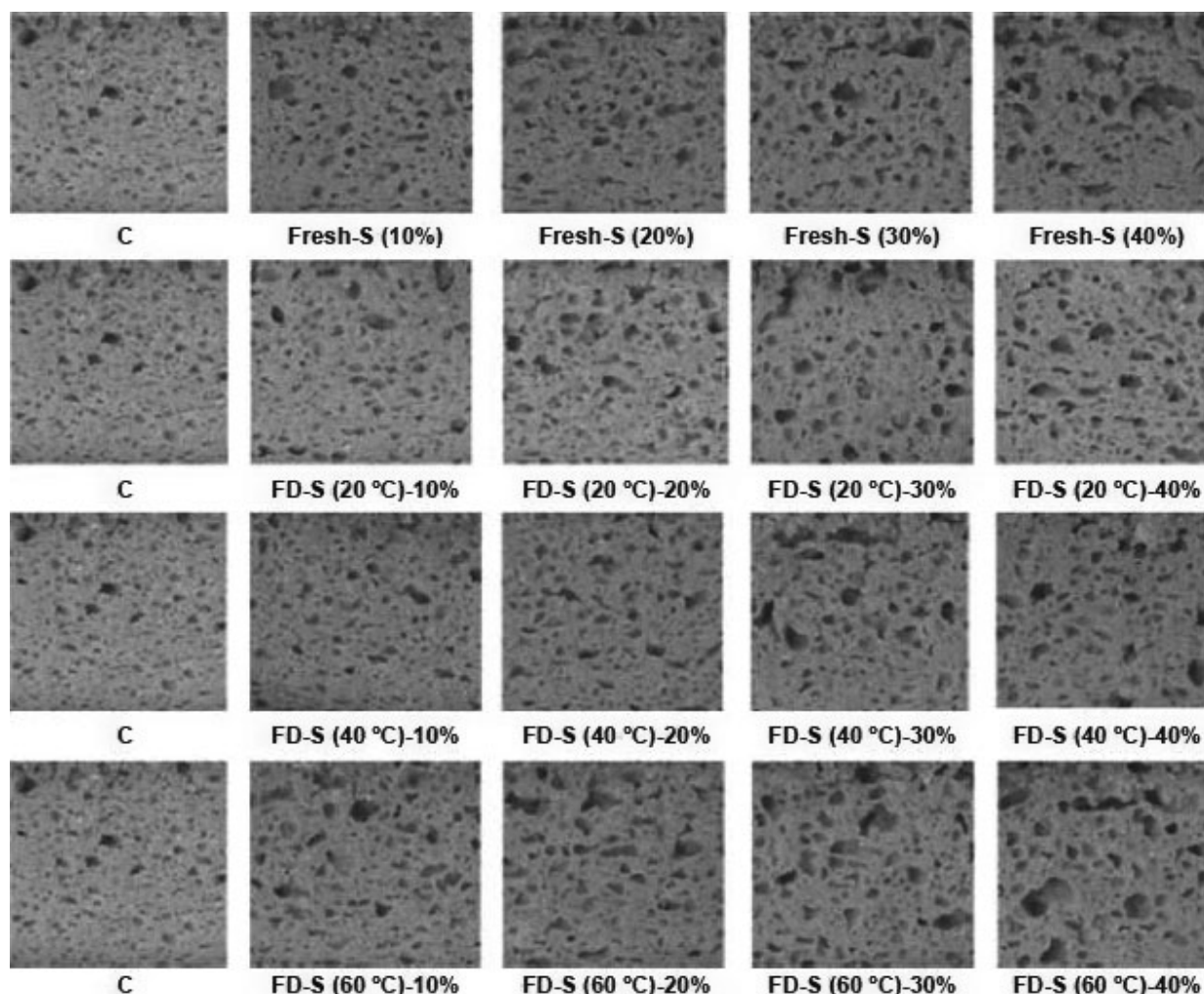


Figure 2 General view of gluten-free bread crumb made with different levels of fresh (Fresh-S) and freeze-dried buckwheat sourdough (FD-S) compared with the control (C). Source: Różyło *et al.* (2015).

and taste of GF breads. For instance, fermentation may increase the viscosity of sourdough leading to stable crumb structure and extended shelf life (Wolter *et al.*, 2014a; Axel *et al.*, 2015; Marti *et al.*, 2015; Różyło *et al.*, 2015; Rizzello *et al.*, 2016).

Transgenesis

Transgenesis of durum wheats was another way to utilise wheat in GF products using either biolistics or agrobacterium-mediated systems. This allows both the addition of novel genes and the downregulation of endogenous genes using RNAi technology. The breeding of low-immunogenic wheat varieties requires selection and crossing from varieties, accessions and wild relatives. The usage of advanced transgenesis techniques to eliminate gluten genes, such as CRISPR/Cas9 technology, and silence the expression of gluten genes was explored (Gilissen *et al.*, 2015). A biolistics approach

was applied to downregulation of α -gliadin genes in hexaploid wheat. Becker *et al.* (2012) reported that major reductions in the α -gliadins do not cause major differences in flour functionality with only a slightly detrimental effect in microbaking tests. Alteration of protein structure has also been achieved through genetic manipulation of specific gluten proteins to reduce the gluten immunoresponse (Gil-Humanes *et al.*, 2014a) by reducing the gliadin content by up to 97%. The transgenesis technological properties of doughs prepared from the low-gliadin lines might be applied to other nontoxic cereals, as raw material to produce GF products (Gil-Humanes *et al.*, 2014b).

Enzyme technology

Enzymes have been used in GF production (Tsatsaragkou *et al.*, 2014). Enzymes such as transglutaminase (TGase), maltogenic amylase, α -amylase,

thermolysin and amyloglucosidase have been used to enhance protein functionality, improve dough handling and bread quality. Research shows that with the addition of amylolytic enzymes (α -amylase and amyloglucosidase), the volume of a quinoa-based bread increased by 23% compared to the control, while with α -amylase itself, the firmness of the bread was highly improved (Elgeti *et al.*, 2014). Fungal amylase, esterase, hemicellulase, glucose oxidase and transglutaminase were used to investigate the effects on pasting properties of flour and texture profiles of the dough. The result showed that fungal amylase enzyme consistently affected the flour properties. However, the enzyme activity consistently decreased the overall viscosity during heating, shearing and cooling cycle and caused reduction in the firmness of the dough (Palabiyik *et al.*, 2016).

The germination of cereal and pseudo-cereal grains can lead to a drastic increase of α -amylase. Rice flour with 48 h of germination produces a significant softness in bread crumb, but also results in an excessive liquefaction and dextrinisation causing inferior bread quality (Cornejo & Rosell, 2015). In a research of Mäkinen *et al.*, germination of oat presented a drastic increase in α -amylase activity from 0.3 to 48 U g⁻¹, and minor increases in proteolytic and lipolytic activities. However, the overdosing of oat malt deteriorated the product because of the excessive amyolysis during baking (Mäkinen *et al.*, 2013).

With more attention paid on GF products, some new method has been explored. van Riemsdijk *et al.* (2011a) suggested that gluten could be replaced by mesostructured whey protein particles. They built the mesoscopically structured whey protein system and observed that the replacement changed the starch mixture from a liquid into a cohesive material, having strain-hardening properties (van Riemsdijk *et al.*, 2011b). Torres *et al.* (2017) reported some methods to enhance antioxidant activity of GF baked products by incorporating natural bioactive compounds such as starchy materials and its by-products, spices, herbs, green plant and fruits, including their seeds. However, extensive consumer testing must be performed to evaluate sensory acceptance.

Conclusion and future research

A lack of gluten typically adversely influences GF products' textural, baking and sensory properties. There are various methods that could be applied to improve the quality of GF bakery and pasta products. The most widely used method is using alternative flours and food additives. From Tables 1-3, the uses of rice and corn are more predominant than other substitute flours and starches. For GF products made of

rice or corn, a combination of starch gelatinisation and protein denaturation is important as it could help build a compact structure to increase the firmness of GF products. Other GF cereal flours such as buckwheat, amaranth, quinoa, teff and oat could provide fibre, vitamins and minerals to final GF products. Often alternative wheat flour substitutes alone cannot achieve satisfying texture of GF products. Other additives are needed in the production of GF bakery and pasta products. Hydrocolloids are commonly used to improve firmness of bakery products and cooking behaviour of pasta. Alternative proteins such as egg protein could improve colour and texture of bakery products and stabilise internal structure of pasta.

Various heating and processing steps have been applied to improve quality of GF products, for instance, infrared-microwave combination heating provides better texture and sensory qualities of bread, while extrusion cooking improves firmness of cooked pasta. Bioprocessing fermentation is an effective way to modify the GF dough, which can help improve the texture for GF products. Enzymes and lactic acid bacteria such as transglutaminase, α -amylase and *Lactobacillus sanfranciscensis* have been used in sourdough which could improve the texture of final GF products. Transgenesis of durum wheat is another novel way to improve the overall quality of GF bakery and pasta products, although it is not able to reduce all the gliadin in wheat. Further research is needed to demonstrate whether the transgenic wheat is safe to be consumed by consumers with CD.

For the past decade, in spite of considerable efforts to offer acceptable GF bread and pasta products to consumers, there are much more room to improve their quality characteristics to match those made with wheat and its products. Hence, the combination of raw materials, functional additives and processing technologies can synergistically serve this purpose and needs extensive further research. Additionally, improving nutritional quality of GF bread and pasta products is necessary to improve the health of CD consumers. Research on enhancing antioxidant properties of GF baked products by incorporating natural bioactive compounds has already been on the way.

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