A REVIEW: UNDERSTANDING GLUTEN FREE BREAD DEVELOPMENT FOR REACHING QUALITY AND NUTRITIONAL BALANCE

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ABSTRACT

Gluten free foodstuff development has attracted in the last decade great attention due to better diagnoses of coeliac disease and common chatters about the relationship of gluten free products with healthiness. The increasing interest has prompted an extensive research for developing gluten free foodstuff resembling gluten containing foods. Different ingredients, additives, processing aids and even diverse breadmaking conditions have been reported for building up network structures enabling fermentation and baking and giving acceptable gluten free breads. This review aims to get some insights on the key points when developing gluten free bread regarding ingredients, additives and the process conditions and to point out recent researches dealing with nutritional composition of those products.

Keywords: gluten free, bread, dough, process, raw materials, nutrition, quality.

INTRODUCTION

A few years ago, gluten-free products were virtually unheard of except in specialty health food stores. Whatever is the real motivation to consume gluten free foodstuff, nowadays a rising demand for gluten-free products is observed in the market trends. The market for gluten-free foods and beverages has continued to grow even faster than anticipated.

‘Gluten-free’ has become an identity for the tens of millions of Americans who have reduced or eliminated their consumption of wheat, barley, rye, and oats. While growth rates will moderate over the next five years in the wake of market expansion, Packaged Facts projects that U.S. sales of gluten-free foods and beverages will exceed $6.6 billion by 2017. [1] Trend data shows the gluten-free target audience to be 44 million strong. North America is the largest market for gluten-free products accounting nearly 59% of the market share in 2012. Major demand in the market is anticipated to come from countries such as U.K., Italy, U.S., Spain, Germany, Australia, Brazil, Canada, India, etc. [2] The increasing interest has promoted the launching of hundredth of gluten free foodstuff, being a niche market with steady growing shares.

Those trends have been accomplished by numerous research studies on the topic of developing gluten free breads, as recent reviews pointed out. Specifically, Moroni et al.[3] focused the attention on the sourdough role in gluten free breadmaking, showing that sourdough fermentation positively influences all aspects of bread quality: texture, aroma, nutritional properties and shelf life. The extent of the effect was really dependent on the microbiota of the sourdough used, and they open the possibility to obtain natural products with a reduced use of additives or even clean labels. Later on, Cabrera-Chávez and Calderón de la Barca [4] reviewed the use of sourdough with the purpose of modifying the immunogenic sequences of gluten to avoid recognition by the immune system and to prepare safe and acceptable foods. Besides the use of the sourdough, the effect of long-time fermentation and enzymatic derivatisation of immunogenic gluten peptides by transamidation using microbial transglutaminase were some of the approaches reported to reduce gluten immunogenicity.

Houben et al. [5] reviewed the possibilities to increase the baking quality of gluten-free bakery products, by describing the ingredients, namely flours and starches, hydrocolloids and gums, proteins, enzymes, fats and emulsifiers and sourdoughs that have been reported in gluten free bread development. A good description of the role of each ingredient and additive in gluten free breadmaking and their reported effect on the bread quality are included in that review. Simultaneously, Zannini et al. [6] reviewed the advances in the preparation of high-quality gluten free breads using gluten free flours, starches, hydrocolloids, gums, and novel functional ingredients.

Additionally, analytical methods for gluten detection have been an active area of debate pertaining immunochemical and non-immunochemical assays developed for gluten quantification, their sensitivity, specificity, cross-reaction and their feasibility for testing gluten-free food consumed by patients with coeliac disease. [7-8]

Previous reviews showed the extensive research dealing with gluten free foodstuff and the tools that food technologist have been using for developing gluten free breads. Nevertheless, there is still a gap regarding the fundamental basis for building up gluten free bread and moving forwards their nutritional pattern. The objective of this review was to get some insights on the key points when developing gluten free bread regarding ingredients, additives and the process conditions and to point out recent researches dealing with nutritional composition of those products.

Gluten definition and its technological importance

Numerous explanations have been reported for defining gluten, which greatly vary if the discipline was within food science or medicine. In January 2009, a European Commission Regulation [9] on gluten free foods was adopted based on the Codex Standard 118-1979. [10] In the context of gluten intolerance and for the purposes of this Regulation the 'gluten' means a protein fraction from wheat, rye, barley, oats or their crossbred varieties and derivatives thereof, to which some persons are intolerant and which is insoluble in water and 0.5M sodium chloride solution; and 'wheat' means any *Triticum* species. While 'foodstuffs for people intolerant to gluten' means foodstuffs for particular nutritional uses which are specially produced, prepared and/or processed to meet the special dietary needs of people intolerant to gluten. [9]

Additionally, gluten is a complex group of seed storage proteins of cereals, which account for a high percentage of the cereal protein content. In general, gluten contains two main protein fractions, prolamins which contribute essentially to the viscosity and extensibility of the dough system, and glutenins which are responsible for dough strength and elasticity. [11] The combination of these two fractions results in the gluten complex; which becomes apparent when flour is hydrated, leading to an extensive dough, with good gas holding properties and good crumb structure in baked bread. Gluten, therefore, exhibits cohesive, elastic and viscous properties that combine the extremes of the two components. Gluten is often termed the 'structural' protein for breadmaking. In contrast, gluten- free doughs are unable to develop a similar protein network owing to differences in the protein properties. A very comprehensive approach for understanding the protein interaction in gluten and gluten free doughs, based on maize zein, has been recently reviewed by Erickson et al. [12] Consequently, the replacement of the gluten network in the development of gluten-free bread has been largely a bottleneck to answer the requirements of people intolerant to gluten.

Consequences of lack of gluten in dough and foodstuff

Baking without gluten is a big challenge for all bakers and cereal researchers. The absence of gluten in dough production shows high influence on dough rheology, the production process and the quality of the final gluten-free products. The gluten-free doughs are much less cohesive and elastic than wheat dough. They are highly smooth, sticky, less elastic and difficult to handle. In fact, these gluten-free doughs are often called batters instead of dough. [5] The absence of gluten often results in baking bread with a crumbling texture, poor colour and other quality defects post-baking. [13] Additionally, because of their low ability to hold the carbon dioxide released during proofing, the volume of the products are rather low. A short shelf life, particles detection in the mouth during consumption, a dry mouth feeling and a not really satisfying taste are also some of the disadvantages of gluten-free bread. [5] Therefore, in the last years numerous studies have been focused in improving the quality of gluten-free foods, particularly fermented and baked foods like bread. [14-21]

In spite of the efforts of bakers and scientists to obtain gluten-free breads of good quality, the manufacture of baked goods without gluten results in major technological problems. In fact, many gluten-free bread available on the market are often of poor technological quality, exhibiting low volume, poor colour and crumbling crumb, [22] besides great variation in the nutrient composition, with low protein and high fat contents,[23] particularly when compared to their wheat counterparts. [24]

Developing gluten free products

Coeliac disease increasing diagnosis and market trends have prompted an extensive research for the development of gluten-free bread (see review Houben et al.[5]). Traditionally, most of the gluten-free products were made of native and modified starches blended with different hydrocolloids (Figure 1). Generally, bread development without gluten has involved the use of diverse ingredients and additives with the purpose to imitate the viscoelastic properties of the gluten and consequently to obtain bread-like products [13] (Table 1, Figure 1). However, to improve the quality of gluten-free breads, diverse ingredients like cereal and pseudocereals flours, hydrocolloids, enzymes and proteins of different sources have been proposed. [5,8] Recently, the nutritional benefits of pseudocereals like amaranth, quinoa and buckwheat have been reviewed besides their use in the formulation of high quality, healthy gluten-free products such as bread and pasta. [25] In recent years, there has been extensive research for the development of gluten-free bread, involving diverse approaches, like the use of different naturally gluten-free flour (rice, maize, sorghum, soy; buckwheat), [16,18,26] and starches (maize, potato, cassava, rice, bean), [27-31] dairy ingredients (caseinate, skim milk powder, dry milk, whey), [32] gums and hydrocolloids (guar and xanthan gums, alginate, carrageenan, hydroxypropyl methylcellulose (HPMC), carboxymethyl cellulose (CMC); [33-36] emulsifiers (DATEM, SSL, soy lecithin), [37-39] other non-gluten proteins (milk proteins, egg proteins, legumes proteins: soy bean and pea); [13-15,21,29,40-41] enzymes (cyclodextrin glycosyltranferases, transglutaminase, proteases, glucose oxidase, laccase) [14-15,42-51] and prebiotics (inulin), [52-54] or combinations thereof; [19] as alternatives to gluten, to improve the structure, mouthfeel, acceptability and shelf-life of gluten-free bakery products. Based on scientific results it is rather difficult to advice about the ingredients, additives and processing aids to be used when developing gluten free bread. A comparison exercise of the improved gluten free breads reported in a certain number of scientific papers has been tried using specific volume and crumb hardness (Table 1). The objective in those papers was rather diverse from determining the effect of gluten free raw materials, some ingredients (fibres and proteins), additives and processing aids (enzymes), up to process conditions. Table 1 displays the great impact of the recipes on specific volume and crumb hardness of gluten free breads and could orientate about the quality of those products.

Staling is one of the main drawbacks of this type of bread due to its main starchy composition. Additives and processing aids have been also tested for extending the shelf-life of gluten free breads. Specifically, alfa amylases, [55] emulsifiers, [39,56] sourdoughs, [3] pregelatinized flours, [56] and inulins. [54] Nevertheless, the anti-staling effect is greatly dependent on the recipes composition.

Apparently and according to these studies, the use of some of these ingredients is essential for reaching higher quality in gluten-free bread. The role of each one of these ingredients and additives has been well clarified in previous reviews. [5,13,57] Nevertheless, up to now it is only clear that hydrocolloids improve the quality of the gluten free breads, but the level of addition of each hydrocolloid depends on the source of hydrocolloid and also on the raw material used for the gluten free recipe. [58]

In general, previous studies have been conducted analysing the dough or batter properties and also the quality parameters of the final breads. Regarding, dough characterization, a wide variety of methods or devices have been used for determining rheological properties, among them fundamental rheology using rheometer [38-39,42,53,59-61] and empirical rheology through the use of the Brabender Farinograph, [26] rapid viscoanalyzer or RVA [26] and Mixolab, [14,19,32,52,59-60] but no concluding remarks have been established about the advisable properties for the gluten free doughs. About bread characterization, usually instrumental parameters are generally assessed like specific volume and crumb texture, but also crumb colour, digital crumb analysis, and water activity. In some studies, sensory attributes have been defined and used for assessing gluten free bread quality [22] and lately the nutritional composition. [23,52]

However, there is no guide or fundamental knowledge to scientifically design gluten free products based on the relationships between dough characteristics and bread quality. Because of that, a revision of the scientific literature, dealing with gluten free both dough and bread level, will be really useful to decipher possible parameters that could predict quality of the final bread. Recently, some attempts have been reported for identifying those potentially useful parameters. In fact, Matos and Rosell [19] designed and assessed six rice flour based gluten-free formulations. In that study, recipes containing mainly rice flour or rice flour combined with potato and corn starches, and others ingredients like protein sources (skim milk powder, whole egg powder, or soy protein isolate) and hydrocolloids (xanthan gum, HPMC, or pectin) were used for the production of gluten-free breads. These, different gluten-free rice formulations were initially selected to cover a range of gluten-free doughs with different rheological features, and in consequence, gluten-free breads with diverse technological and sensorial quality. Results showed that in general, several relationships were found among the rheological properties of formulated gluten-free dough/batter, measured with the Mixolab, the instrumental quality parameters and sensory characteristics of the bread-like products. Strong correlation coefficients (r >0.70) were found when quality instrumental parameters of baked products were correlated with the dough Mixolab® parameters, and moderate correlation coefficients (r <0.70) were found with sensory characteristics. Dough consistency during mixing (C1), amplitude and dough consistency after cooling (C5) would be useful predictors of crumb hardness; and C5 would be also a predictor of perceived hardness of gluten-free bread-like products.

With the same objective, data of dough characteristics and bread quality from very diverse reported recipes have been compiled to understand their possible relationship.

The most common parameters used for assessing gluten free dough/batter properties have been viscoelastic moduli, pasting properties and Mixolab parameters; in consequence those have been pooled and correlated with specific volume and crumb texture parameters. Table 2 displays the significant correlations found between dough parameters obtained during the heating and cooling cycles with the Mixolab and the instrumental quality parameters (specific volume and TPA-hardness) of 35 gluten free breads. Although various significant correlations were found, only strong (r >0.7) or moderate (0.4< r <0.7) correlations were considered. Specific volume showed strong and negative correlation with crumb springiness (r = -0.7224) and moderate with hardness (r = -0.5529) and cohesiveness (r = 0.4861). The relationships between the TPA-hardness and C1, C5 and gelling (C5-C4) parameters were strongly significant (P <0.001) and positive and was moderate with C4 (r = 0.4791). This could indicate that the TPA-hardness values are strongly correlated (r >0.70) with parameters characterising hydration and cooling consistency, which agrees with previous findings of Matos and Rosell. [19] In addition, cohesiveness was highly correlated with C1, and gelling (C5-C4), although their effects were opposite. Cohesiveness was negatively correlated with C1 and positively correlated with gelling. Conversely, springiness was strong positively correlated with C1 and negatively with gelling parameter.

When the same analysis was carried out with the viscoelastic moduli reported for 25 different gluten free doughs, significant correlations were not obtained either with specific volume or crumb textural parameters. Neither significant correlations were found between pasting parameters determined with the Rapid Viscoanalyzer (RVA) and bread texture parameters, likely due to the low number of data available from published manuscripts.

In consequence dough consistency after mixing and also the consistency increase after baking are crucial in determining crumb textural parameters.

Process advances in gluten free breadmaking

Lately, research is also focussed on modifying the existing raw materials for improving its adequacy to gluten free breadmaking. In gluten-free bread productions, the most used modified starches are the cross-linked, starch esters, partial complex bounded or pregelatinized starches and mechanically treated or extruded starches. [62] They are used as a thickening agent; in addition, they stabilize the crumb structure and can decrease retrogradation. [5] The application of extrusion to rice flour for promoting starch gelatinization has been proposed by Pedrosa Silva Clerici et al. [63] After varying the extrusion temperature and the concentration of lactic acid, acidic extruded rice flour was obtained, which was blended (10%, rice flour basis) with rice flour. The gluten free breads obtained showed similar crust and crumb texture than those of wheat breads.

De la Hera et al. [61,64] pointed out the importance of particle size on flour functional properties and gluten free breadmaking. Particularly, the particle size of corn flour influences significantly the dough development during proofing, with better behaviour of the coarse flour (>150μm), and in consequence, the final volume and texture of the breads. [61] Similar results have been also obtained when using rice flour for gluten free breadmaking. [65]

Gluten free breadmaking is also different than the gluten containing foods, mainly owing to the restrictions associated to the amount of water, which is responsible of the dough consistency during mixing, [15] but also affects dough fermentation. [66] In doing so, mixing arm also influences dough development and gluten free bread quality. Gomez et al. [66] found that when dough hydration was 80% the mixing arm type did not have any significant effect, but high specific volume was obtained with longer mixing time. Conversely, when using 110% dough hydration the mixing arm (wire whip, flat beater or dough hook) and mixing speed had a significant effect on bread volume and texture, achieving higher specific volumes and softer breads with the wire whip with low mixing speed (speed 2) and long mixing time (8 min). Moreover, low hydrated dough had low ability to retain gas released during proofing, whereas high hydrated doughs (110%) endure longer fermentation time and that resulted in improved specific volume (Gomez et al., 2013).

Gluten free breads are mainly starchy matrixes where the complete gelatinization of the starch has great effect on the bread quality. Starch gelatinization can only be ensured if enough water is present, because of that very often gluten free doughs resembled more to batters. In addition, when gelatinized starch is present at the initial stages of breadmaking, it can significantly contribute to dough consistency. In fact, Brites et al. [26] made corn gluten free bread applying flour blanching for increasing dough consistency, adhesiveness, springiness and stickiness. Blanching consisted in adding boiling water (77%) to corn flour and after mixing it was left idle till cooling, and then the rest of water and ingredients were mixed, proofed and baked. Flour blanching gelatinized part of the corn starch and that was responsible of the dough textural properties. The same strategy was applied by Marco and Rosell [15] when developing rice based bread.

Partial starch gelatinization of the raw material has been also obtained by using high hydrostatic pressure. The strategy initially developed for gluten breads, [67] was applied to sorghum batters in the production of sorghum breads. [68] Pressures comprised between 200MPa and 600MPa were applied to sorghum batters observing that pressures higher than 300MPa gave higher batter consistency due to pressure-induced gelatinization of starch. The replacement of 2% sorghum flour with 600MPa treated flour delayed the staling of the breads, but higher addition of pressure treated flour resulted in low specific volume and poor bread quality.

The effect of ovens has been also a subject of study with gluten free breads. Demirkesen et al. [69] investigated the effect of different blends of tigernut flour:rice and compared the quality of the breads baked in conventional ovens and infrared-microwave combination. Conventionally baked breads had higher gelatinization degrees (from 92% to 94%) than the infrared-microwave combination baked breads (from 84% to 88%); and they explained that result due to processing time is longer in conventional oven. However, the gelatinization degree reached with both types of ovens was sufficient to obtain gluten free breads.

Moreover, related to baking alternatives, Sciarini et al. [35] reported the use of partial baking process on gluten free bread quality. Instead of baking in one step, the part-baking process consisted in baking up to 63% of the time employed in the conventional baking and the full baking was finished whenever necessary after keeping the part-baked product stored at low temperatures. Nevertheless, authors found that breads from two steps baking had lower specific volume and higher crumb hardness with small gas cells, and also showed higher amylopectin recrystallization than breads obtained with a one stage baking. Those negative effects were partially mitigated by the hydrocolloid addition (CMC and xanthan gum).

Nutritional quality of gluten free products

Studies on gluten free products, particularly bread, have been concentrated on improving technological parameters (volume, crumb hardness, and so on) besides sensorial perception. However, the nutritional concept of the gluten free baked goods has been scarcely addressed. Historically, nutrition counselling for celiac disease has focused on the foods to avoid gluten in the diet. There is growing concern over the nutritional adequacy of the GF dietary pattern because it is often characterized by an excessive consumption of fats and reduced intake of complex carbohydrates, dietary fibre, vitamins and minerals. [23,70]

Recently, some nutritional aspects of selected commercial gluten-free products including breads have been assessed. Matos and Rosell [23] evaluate the nutritional pattern of gluten-free breads representative of the Spanish market for this type of products. In general, authors found that the protein, fat and mineral content of the gluten-free breads showed great variation, ranging from 0.90 to 15.5 g/100g, 2.00 to 26.1 g/100g and 1.10 to 5.43 g/100g, respectively; and as consequence had very low contribution to the recommended daily protein intake, and a high contribution to the carbohydrate dietary reference intake. Additionally, dietary fibre content showed great variation (1.30 to 7.20 g/100 g). Mentioned authors suggested that the gluten-free breads showed great variation in the nutrient composition, being starchy based foods low in proteins and high in fat content. Lately, gluten free formulations are being set up considering the nutritional quality of the final gluten-free baked products. The most common strategy to increase the nutritional value of gluten-free breads is to include nutritionally valued raw flours. Although those flours are often presented as new crops and raw material, they have been used by local populations in traditional ways for many centuries. Consequently, their innovation is related to the ways in which old and new uses are being readdressed. [71] Non-traditional flours such as pseudocereals flours (amaranth, quinoa and buckwheat), root and tubers flours (such as potato, cassava, sweet potato and edible aroids: taro and yams), and leguminous flours (chickpeas, lentils, dry beans, peas, and soybean) [72] are gaining popularity in the production of gluten-free foodstuff with major nutritional quality.

Particularly, pseudocereal flours such as buckwheat, [17-18,46,73-75] amaranth, [76] and quinoa [74,77] have been used in several formulations. Other raw materials such as sorghum flour, [30-31,46,74,78] carob germ flour, [79] chestnut flour, [59-60] tigernut flour [69] and teff flour [46,74] have also been used as innovative gluten-free raw materials; and generally, gluten-free breads of good quality have been obtained after optimizing breadmaking recipe. The nutritional quality of flour made from pseudocereals or teff is better than that of wheat flour, but their breadmaking properties and sensory characteristic compromise somewhat their suitability for the production of gluten-free bread. Pseudocereals-containing breads have significantly softer crumb texture, and this effect was attributed to the presence of natural emulsifiers in the pseudocereals flours. Hager et al. [74] compared the breadmaking potential of six gluten-free flours (white rice, maize, teff, sorghum, quinoa, and buckwheat flours) with that of oat, wheat and wholemeal wheat flours. Results revealed that although rice and maize flours are widely used for the production of gluten-free products, when compared to other gluten-free raw materials, their suitability for the production of bread is reduced.

Next to the use of new raw materials, protein enrichment has gained interest and with that aim soy protein isolates and also legume flours or legume protein isolates have been incorporated. [14-15,19,21,41] Generally, the enrichment of gluten free bread in proteins leads to a decrease in both the specific volume and the crumb softness, but despite the detrimental effect on the instrumental quality parameters the nutritional impact was readily evident.

In addition, gluten free foodstuff has not been immune to the new trends in baked products pertaining fibre enrichment. Fibre sources such as rice bran [20] and inulin [52] have been added in gluten-free breads with the consequent improvement in the nutritional quality. Very recently, *Psillium* gum and sugar beet fibers have been added to gluten free breads, [80] and water adsorption must be adapted due to the fibres water binding ability. Those fibres improved the workability of the doughs, but mainly *Psillium* thanks to its film forming ability contributed to bread development and had more effective anti-staling result.

The level of micronutrients in gluten free breads has been also a point of attention. Suliburska et al. [81] determined the content and release of minerals (Ca, Mg, Fe, Zn and Cu) from selected gluten-free products (bread, biscuits, pasta, corn porridge and peas puff) of the Poland market. Results showed that the content of minerals varied considerably among the types of products, and it was relatively low. Among the analysed products, bread was characterised by a high content of calcium and zinc, and relative high content of magnesium. However, bread showed the lowest content of iron and copper. Moreover, the potential bioavailability of minerals from gluten-free products was in the range 10-70%, and it depended on the element and the composition of the analysed product. Authors concluded that it should be consider the enrichment of gluten-free products in minerals. In fact, that point has been addressed in several researches dealing with the supplementation of vitamins and minerals in gluten free breads. Kiskini et al. [82] studied the feasibility of producing gluten-free bread fortified with iron using selected iron compounds. The most acceptable products were those fortified with ferric pyrophosphate, which showed satisfactory sensory and nutritional characteristics. A more recent research [32,52] was focused on the fortification of gluten-free bread containing inulin, with different organic and non-organic calcium sources. All experimental breads were significantly richer in calcium compared to the control, confirming the fortification. Additionally, sensory evaluation of the calcium-fortified breads confirmed that calcium carbonate was the most recommended salt for obtaining calcium fortification of gluten-free breads.

Good glycemic control is particularly important in celiac disease, as there appears to be a higher incidence of type I diabetes among coeliac disease patients. [83] However, limited studies have been focused on assessing the glycemic index (GI) of the gluten-free products. [23,83-84] Overall, pseudocereals such as quinoa and amaranth have shown some hypoglycaemic effects, and have been recommended as an alternative to traditional ingredients in the formulation of cereal-based gluten-free products with low GI. [77,83] Contrarily, starch-based gluten-free breads have shown estimated glycaemic index values between 83.3 and 96.1, thus these types of breads could be considered as food with high glycaemic index. [23] Therefore, it is necessary to choose suitable materials when formulating gluten-free products to reduce the GI in the developed products.

CONCLUSION

Many researchers have been focussed on the development of gluten free breads trying to overcome the challenge of gluten absence with more or less fortune. A range of ingredients, additives and processing aids are available for obtaining good quality products, but also process conditions plays a key role in this type of products. The design of gluten free breads remains an empirical task but some conclusions must be drawn from all the rheological and quality studies. The compilation of results from scientific literature reveals that TPA textural parameters of gluten free crumbs are strongly correlated with dough consistency and starch retrogradation or gelling, specifically, low dough consistency and low gelling values are related to softer crumbs.

However, nutrition remains a bottleneck in these type of products, although, as has been mentioned before, some recent papers have been highlighted this topic. Nutrition is, moreover, really important point since the gluten free dietary pattern is often characterized by an excessive consumption of proteins, and fats, and a reduced intake of complex carbohydrates, dietary fibre, vitamins and minerals. Therefore, it is necessary to have a holistic concept when developing gluten free breads, considering, instrumental quality, sensory and nutrition.

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FIGURE CAPTIONS

Figure 1. Rice based gluten free breads and their crumb cross-sections obtained from different recipes. HPMC K4M (1, 3); Xanthan gum and guar gum blend (2, 4); Pea proteins (1, 2), albumin (3, 4). Courtesy of R. Garzón.

Table 1. Specific volume and hardness of gluten free breads previously reported.

	Aims	Specific volume (mL/g)	Hardness (N)	
Raw materials	Additives combination	1.90 ± 0.11	2.25 ± 0.23	Pongjaruvat et al. [85]
	Corn varieties	1.12 ± 0.01	163.35 ± 10.52	Brites et al. [26]
	Flour particle size	2.84 ± 0.02	6.11 ± 0.05	de la Hera et al. [61]
	rice, maize, teff, and buckwheat	1.80 ± 0.05	18.80 ± 1.90	Hager et al. [74]
	high pressure treated oat flour	1.58 ± 0.06	12.49 ± 0.53	Hüttner et al. [57]
Proteins		4.70 ± 0.20	0.60 ± 0.10	Ziobro et al. [21]
Fibers	Psyllium and sugar beet fibers	2.70 ± 0.26	12.14 ± 1.72	Cappa et al. [80]
Processing aids	Protease	2.81 ± 0.01	0.68 ± 0.01	Kawamura-Konishi et al. [50]
	cyclodextrin glycoxyl transferase	4.60 ± 0.02	17.90 ± 0.03	Gujral et al. [42]
	Protease	2.98 ± 0.11		Hamada et al. [51]
	amylases	1.85 ± 0.05	23.50 ± 0.50	Gujral et al. [55]
	transglutaminase	2.75 ± 0.21	51.25 ± 1.02	Gujral and Rosell [43]
	glucose oxidase	2.65 ± 0.05	25.51 ± 0.54	Gujral and Rosell [44]
Process	Mixing type	5.23 ± 0.05	0.38 ± 0.01	Gomez et al. [66]
Additives	Hydrocolloids	3.57 ± 0.22	0.27 ± 0.03	Mariotti et al. [75]
	Emulsifiers	2.21 ± 0.06	12.10 ± 2.01	Nunes et al. [38]
	Additives combination	2.71 ± 0.02	1.95 ± 0.03	Marco and Rosell [15]
	Additives combination	2.65 ± 0.15	16.98 ± 1.66	Phimolsiripol et al. [20]
	Additives combination	2.38 ± 0.09	13.50 ± 0.10	Sciarini et al. [39]

Table 2. Correlation matrix between instrumental quality parameters of gluten-free breads and dough/batter rheological parameters determined with the Mixolab®.

	Hardness	Cohesiveness	Springiness	Resilience	C1	C2	C4	C5	Gelling (C5-C4)
Specific volume	-0.5529***	0.4861*	-0.7224***						
Hardness					0.8211***		0.4791**	0.7533***	0.8112***
Cohesiveness				0.7522***	-0.7253**			0.5568*	0.8204***
Springiness					0.8017***				-0.6682
C1						0.7124***	0.4981***	0.5549***	
C2							0.4891***	0.4888**	
C4								0.8961***	

Correlations indicated by *r* values. ****P*-value <0.001, ***P*-value <0.01, **P*- value <0.05.

C1: initial consistency; C2: minimum torque; C4: minimum torque during the heating period; C5: torque obtained after cooling at 50ºC.

Figure 1.