



Functionality of alternative protein in gluten-free product development

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Abstract

Celiac disease is an immune-mediated disease triggered in genetically susceptible individuals by ingested gluten from wheat, rye, barley, and other closely related cereal grains. The current treatment for celiac disease is life-long adherence to a strict gluten-exclusion diet. The replacement of gluten presents a significant technological challenge, as it is an essential structure-building protein, which is necessary for formulating high-quality baked goods. A major limitation in the production of gluten-free products is the lack of protein functionality in non-wheat cereals. Additionally, commercial gluten-free mixes usually contain only carbohydrates, which may significantly limit the amount of protein in the diet. In the recent past, various approaches are attempted to incorporate protein-based ingredients and to modify the functional properties for gluten-free product development. This review aims to highlight functionality of the alternative protein-based ingredients, which can be utilized for gluten-free product development both functionally as well as nutritionally.

Keywords

Bakery products, celiac, food proteins, mechanical properties, microstructure

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INTRODUCTION

Celiac disease (CD) is an autoimmune enteropathy triggered by the ingestion of gluten-containing grains (wheat, barley, rye, and possibly oats) in genetically susceptible individuals (Catassi and Fasano, 2008). The prevalence of CD worldwide is increasing and affecting almost 1% of the population (Fasano and Catassi, 2001). Thus, with the increasing numbers of people intolerant to gluten, the need is rising for high-quality gluten-free products. Additionally, gluten-free products are seeing a growing demand, due to the increase in the incidence of pathologies of various type, all linked to some form of intolerance to gluten (Catassi and Fasano, 2008; Fasano and Catassi, 2001). Presently, the only treatment for CD consists of a life-long gluten-free diet (Gallagher et al., 2004).

In this regard, gluten-free products are of high interest for people suffering from CD and are in need of

strict gluten-exclusion diet. In the past, various authors have investigated the application of starches and hydrocolloids in the gluten-free product development (Calvin Onyango et al., 2013; Lazaridou et al., 2007; Matos Segura and Rosell, 2011; Miyazaki et al., 2006; Rühmkorf et al., 2012). However, various authors have reported that many of the gluten-free products currently on sale are of inferior quality (Alvarez-Jubete et al., 2010; Gallagher et al., 2004; Mariani et al., 1998; Simpson and Thompson, 2012; Thompson et al., 2005). Commercial gluten-free mixes usually contain only carbohydrates, which may significantly limit the amount of protein in the diet (Matos Segura and Rosell, 2011). The inferior quality of gluten-free products can be related to the difficulty in gluten replacement as well as the low nutritional value of such

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products. Distinctly, gluten plays a significant part in development of three-dimensional network, which plays a critical role in textural as well as sensorial properties of the bakery product (Lee and Mulvaney, 2003). Thus, these divergences have prompted the development of alternative gluten-free baked goods in which nutritional quality acquired special relevance (Marco and Rosell, 2008c).

Thus considering the above-mentioned points, enrichment of gluten-free mixes with protein has its important role as a structure and texture-forming agent. Additionally, a common practice in food processing is the incorporation of protein ingredients in product formulation to increase product qualities such as flavour, texture and storage stability apart from increasing its nutritional value (Błaszczak et al., 2006; Storck et al., 2013). During the initial years, the intention of addition of proteins was to enhance the nutritional value of gluten-free products. Lately, it has been also reported that the formation of a continuous protein phase is critical for obtaining an improvement in the quality of gluten-free products (Krupa-Kozak et al., 2013; Marco and Rosell, 2008b; Marti et al., 2014; Matos et al., 2014; Moore et al., 2004). Therefore, the selection of the source of protein with desired functionality can play a significant role in the area of gluten-free product development. Additionally, proteins can form a network-like structure with gluten-free cereal proteins that could hold the dough structure during proofing, resembling the gluten network obtained in wheat bread dough (Marco and Rosell, 2008c).

In recent times, the use of non-gluten protein source has been used in developing gluten-free dough having desirable viscoelastic properties (Erickson et al., 2012; Matos et al., 2014; Storck et al., 2013; Ziobro et al., 2013). The incorporation of protein-based ingredient in gluten-free dough can be highly functional and nutritional benefits. Different protein sources can be added for improving the nutritional quality of gluten-free products, given that CD in some cases leads to malnutrition (Marco and Rosell, 2008c). Especially, dairy and soybean proteins are the most used proteins in gluten-free bread formulations (Gallagher et al., 2003b; Marco and Rosell, 2008c; Ribotta et al., 2004). In addition, applications of protein from legumes sources are also being utilized for the development of gluten-free products (Gularte et al., 2012; Miñarro et al., 2012). Legumes act as a beneficial flour to supplement along with cereal-based flour since both legume and cereal proteins are complementary in essential amino acids (Iqbal et al., 2006). Figure 1 shows different non-gluten-based protein used in gluten-free product development. As seen from the figure, there lies immense possibility of incorporating protein from different

sources like dairy, cereal, and legumes to enhance the nutritional profile of gluten-free products in addition to provide structure- and texture-forming properties. Application of non-gluten protein in gluten-free product development will be discussed subsequently in the paper.

The application of gluten-free products with the use of protein from different sources has been a topic of research among different scientific community. Proteins are typically added to gluten-free applications to increase elastic modulus by cross linking, to improve perceived quality by enhancing Maillard browning and flavor, to improve structure with gelation and to aid in foaming (Arendt and Dal Bello, 2008; Gallagher et al., 2003b; Matos et al., 2014; Moore et al., 2004; van Riemsdijk et al., 2011b). In particular, incorporation of protein has been studied in the recent year with reference to gluten-free bread development with improved loaf volume and crumb properties along with improved sensory characteristic (Gularte et al., 2012; Marti et al., 2014; Storck et al., 2013; Ziobro et al., 2013). Table 1 shows the recent application of alternative protein-based ingredients in development of different gluten-free products.

Thus, considering the importance of protein incorporation in gluten-free products, this review aims to discuss the recent advancement of protein functionality for gluten-free product development.

NON-GLUTEN PROTEIN SOURCE

Cereal-based protein

In the last decades, researchers have focused on different approaches to probe the idea to improvise on the development of gluten-free product. Recent work suggests that the concept of functionalizing non-wheat cereal proteins to mimic gluten's viscoelastic nature is promising field particularly in the area of gluten-free bakery product. Abundant work has been done in the field of gluten-free bread by enhancement and creation of innovative formulation and unique methods (Krupa-Kozak et al., 2013; McCarthy et al., 2005; Sanchez et al., 2004; Schoenlechner et al., 2010; Witczak et al., 2010). However, it has been noticed that the basic shortcoming is batter-like consistency of gluten-free dough. This makes the dough systems more vulnerable to collapse during fermentation and proofing and results in large holes in the center of the bread crumb (Schober et al., 2005, 2007). Additionally, for the production of specialized products, which needs shaping of dough-like soft pretzels, baguettes or braided breads become increasingly difficult.

In the context of above-mentioned current limitation, cereal-based protein-like zein and Kafirin can be highly advantageous due to their ability to form wheat

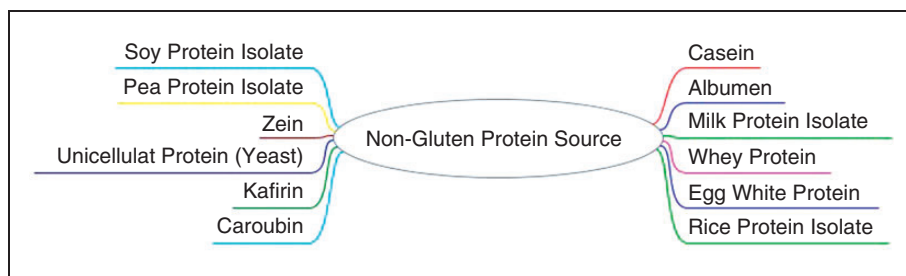


Figure 1. Different sources of non-gluten protein for gluten free product development.

Table 1. Application of alternate protein in gluten-free product development

Sr. No	Protein source used	Gluten-free product	Key observation	References
1	Casein and albumin protein isolates	Bread	Improved crumb texture and better specific volume	Storck et al. (2013)
2	Soybean and pea protein isolates	Fermented products	Increase in the water absorption. Modification of the mechanical and surface related textural properties	Marco and Rosell (2008)
3	Milk protein isolate and novel rice starch	Bread	Dairy protein and rice starch addition increased loaf volume	Gallagher et al. (2003)
4	Egg albumen and whey proteins	Pasta	Improvement in pasta appearance with low cooking loss	Marti et al. (2014)
5	Albumin, collagen, pea, lupine and soy protein	Bread	Soy protein and collagen reduced specific volume. Lupine and albumin increased specific volume	Ziobro et al. (2013)
6	Soy protein isolate and egg white solids	Bread	Improved loaf volume	Crockett et al. (2011)
7	Pea isolate	Bread	Improved specific volume, sensory score	Miñarro et al. (2012)
8	Whey protein particle system	Bread	Improved specific volume and a bubble size comparable with a normal wheat bread	van Riemsdijk et al. (2011b)
9	Albumen	Bread	Improved textural properties and sensory score	Schoenlechner et al. (2010)
10	Pea, soybean, egg albumen and whey proteins	Bakery products	Pea, soybean and whey proteins decreased the final viscosity in addition and the peak viscosity	Marcoa and Rosell (2008)
11	Pea isolate	Bakery products	Improved physical (rheological and ultrastructural) and a delay in the staling phenomenon	Mariotti et al. (2009)

(continued)

Table 1. Continued

Sr. No	Protein source used	Gluten-free product	Key observation	References
12	Soy protein isolate, pea protein isolate, egg white protein, casein	Muffin	Casein and egg white protein increased the specific volume of the muffins. Pea protein isolate containing muffins were softer and springier	Matos et al. (2014)
13	Zein (maize protein)	Bread	Zein in presence of hydrocolloid improved the structural and rheological properties of zein with increased specific volume	Andersson et al. (2011)
14	Casein, egg white	Pasta	Improvement in dough viscoelastic properties	Sozer (2009)
15	Unicellular protein	Bread	Low baking loss	Miñarro et al. (2010)
16	Whey protein particles	Bread	Improved bread properties by the ability to form disulphide bonds. Ability to form viscoelastic properties. Mesoscopic protein particle networks can imitate gluten properties	van Riemdijk et al. (2011a)
17	Soy protein isolate	Muffins	Increase in toughness and stiffness of the muffins and moisture retention along with improved sensory score	Hubbell et al. (2007)
18	Soy protein	White sauces	Improved physical stability. No syneresis phenomena and change in color after 15 days of refrigeration storage (4 °C)	Guardaño et al. (2012)
19	Zein	Bread	Wheat-like cohesive, extensible, viscoelastic dough when mixed above room temperature (e.g. 40 °C) with gas holding ability. Improved specific volume	Schober et al. (2010)
20	Zein–Starch	Hearth-type rolls	Improved textural properties	Schober et al. (2008)
21	Zein mixed with high molecular weight glutenin	Gluten-free products	Improved viscoelastic properties	Fevzioglu et al. (2012)
22	Sodium caseinate, milk protein isolate, whey protein isolates,	Bread	Whey proteins increased specific volume and decrease in hardness over time	Nunes et al. (2009)

(continued)

Table 1. Continued

Sr. No	Protein source used	Gluten-free product	Key observation	References
23	whey protein concentrate Carob germ proteins	Bread	Improved viscoelastic properties and high quality gluten-free bread	Smith et al. (2012)
24	Concentrated casein	Bread	The aggregated casein samples produced were more elastic than gluten	Stathopoulos and O'Kennedy (2008)
25	Whey protein isolate, casein	Fresh hand-made tagliatelle	Improved viscoelastic properties	Chillo et al. (2009)

dough-like structure (Andersson et al., 2011; Lawton, 1992). Due to their unique properties, zein and kafirin, in the recent years, has been a subject of research in the application of gluten-free formulation (Erickson et al., 2012; Mejia et al., 2007; Schober and Bean, 2009; Schober et al., 2008, 2010; Smith et al., 2014). This section aims to review the recent findings of cereal-based proteins in the development of gluten-free products.

Zein. It is the storage protein of maize. It is a major protein fraction of maize kernel. Zein is sub-divided into four fractions based on their differential solubility: α , β , γ , and δ -zein. α -Zein is the most abundant fragment constituting 75–85% of the total protein (Larkins et al., 1989). α -Zein has large amounts of hydrophobic residues such as leucine, proline, alanine, and phenylalanine (Gianazza et al., 1977), which explains its significant hydrophobic properties. Commercial zein isolates are comprised almost entirely of α -zeins (Lawton, 2002).

Ability of zein to produce wheat-like dough has been explored in the development of gluten-free bread for individuals suffering from CD (Andersson et al., 2011; Erickson et al., 2012; Johansson et al., 2012; Schober et al., 2008, 2010; Smith et al., 2014). Maize zein, unlike wheat gluten, is not able to form viscoelastic fibrils at room temperature, though can be made functional in this way at higher temperatures (Bugusu et al., 2001; Lawton, 2002). α -Zein is able to form a viscoelastic protein network during mixing, if the protein is held and mixed at 35 °C, which is above its glass transition temperature of ~28 °C at >20% moisture content (Lawton, 1992).

In the recent work, the role of non-covalent interactions in the formation of viscoelastic material from zein was investigated (Smith et al., 2014). The research reflected the concept that the ability of zein to form viscoelastic material (VEM) can be due to the non-covalent interactions between low molecular weight

proteins rather than chemical and physical interactions of extremely high molecular weight protein complexes as found in gluten. Zein may form VEM through non-covalent protein–protein interactions. Authors concluded that the either modifications to zein proteins, by additives or modifications to the proteins themselves to enhance these interactions, might improve the ability of zein to form VEM either alone or in the presence of co-proteins (Figure 2). This research will aid in the future utilization of zein in food and other industrial applications.

In one of the recent works, it was shown that the addition of small amounts of high molecular weight glutenin (HMWG) to zein causes changes in its viscoelastic properties (Fevzioglu et al., 2012). It was shown that incorporation of HMWG increased the extensional viscosities of gliadin and zein sample thereby suggesting that the rheological properties of zein can be improved with HMWG addition. This information opens the way for future investigation on the development of gluten-free products by utilization of viscoelastic properties of dough. Additionally, the report published by USDA notices that, zein-based systems hold great promise in the search for palatable, high-quality gluten-free products (Durham, 2010).

In one of the studies, it was shown that zein–starch dough in absence of hydrocolloids demonstrated inferior bread-making performance while hydrocolloid additions significantly improved bread volume and height (Andersson et al., 2011). Authors concluded that zein could not mimic the properties of gluten on its own, but hydrocolloids did positively affect the structural and rheological properties of zein, which yielded dough similar to wheat dough and bread with increased volume (Figure 3). Additionally, upon baking, bread with an open foam-like structure and increased bread volume was observed by the authors. Thus, role of different hydrocolloid can be investigated in the structural and rheological properties of zein in future.

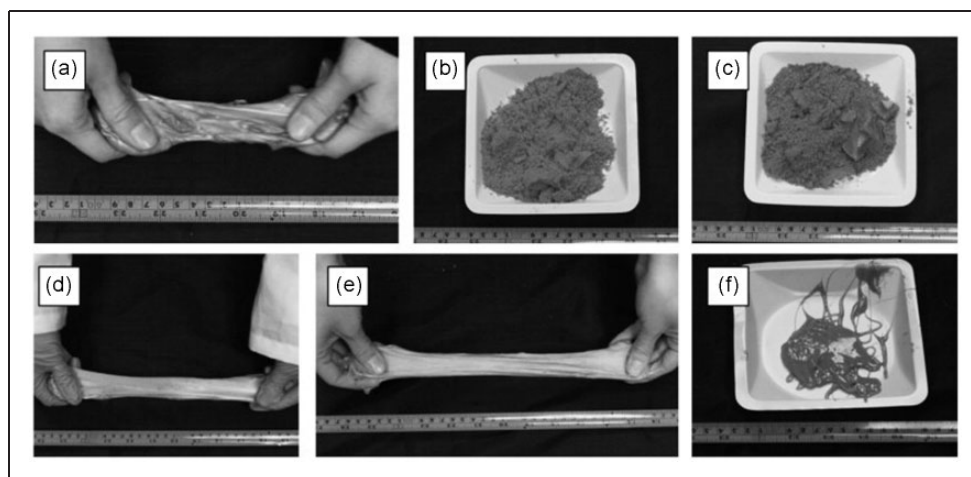


Figure 2. Visual representation of control zein VEM (a) zein treated with 2 M Na₂SO₄ (b) zein treated with 2 M NaCl (c) zein treated with 2% β-ME (d) control wheat gluten (e) wheat gluten treated with 2% β-ME (Smith et al., 2014).

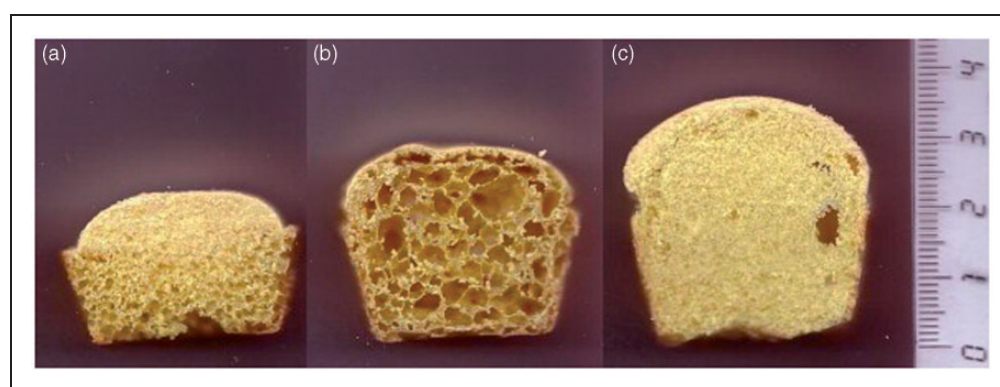


Figure 3. Images of crumb structure for zein-starch mini-breads (a) without hydrocolloids (b) supplemented with 2% OW28 (high β-glucan oat bran (Oatwell®, 28% β-glucan Instant) (c) supplemented with 2% HPMC (Andersson et al., 2011).

In the past, few studies have suggested the possibility of using gluten-free dough from zein and starch having similar extensible rheological behavior as wheat dough. However, studies laid emphasis on the use of hydrocolloid hydroxypropyl methylcellulose (HPMC) to produce quality gluten-free bread with open-like structure and increased specific volume (Andersson et al., 2011; Schober et al., 2008, 2010).

In one of the studies, removal of surface lipids improves the functionality of commercial zein in viscoelastic zein–starch dough for gluten-free bread making (Schober et al., 2010). Defatting of the surfaces of the zein particles helped in the aggregation of zein particle. In this study, maize prolamin (zein), together with starch, HPMC, sugar, salt, yeast, and water formed wheat-like cohesive, extensible, viscoelastic dough when mixed above room temperature (e.g. 40 °C). The dough had a superior ability to hold gas with improved specific volume (4.5 mL/g) and final shape.

In a similar work, commercial zein in presence of HPMC (2 g) significantly improved quality of dough and resulted into bread having a regular, fine crumb grain, a round top, and good aeration (specific volume 3.2 mL/g) (Schober et al., 2008). The study reflected that zein dough could be handled similarly to wheat dough and can be used for the production of specialties like soft pretzels, which are not feasible with traditional gluten-free batters as discussed earlier.

Kafirin. Apart from zein, kafirin also has shown promising result in the area of gluten-free product development (Belton et al., 2006; de Mesa-Stonestreet et al., 2012; Oom et al., 2008; Pontieri et al., 2013; Schober et al., 2011). Kafirin, the alcohol-soluble prolamin protein fraction in sorghum endosperm, makes up about 50% of the grain protein (Paulis and Wall, 1979). Considering the properties of sorghum proteins, it could be an important food alternative for gluten

intolerant and diabetic persons. Kafirins are having a glass transition temperature (T_g) above room temperature at about 28 °C with 20% or higher moisture content (Oom et al., 2008). At these conditions, kafirin can be made to contribute in attaining viscoelastic gluten-free dough development.

Studies on sorghum kafirin have shown it to be analogous in many ways to maize zein (Belton et al., 2006). Kafirins are in general more hydrophobic than average proteins and wheat prolamins (Shewry et al., 2003). On cooking by heating in boiling water, kafirin shows a decrease in their capacity to absorb water due to conformational changes in the protein (Belton et al., 2006). Grain of high digestible, high lysine (HDHL) sorghum contains kafirin, which can enhance the protein network of composite dough (Goodall et al., 2012). This property could be utilized in development of gluten-free composite dough with viscoelastic properties. Although role of kafirin in development of specific gluten-free products has not been investigated so far, but considering its properties analogous in many ways to zein, it can offer a promising solution in the area of gluten-free product development in near future.

In one of the recent studies, impact of different isolation procedures on the functionality of zein and kafirin was studied (Schober et al., 2011). Authors reported that for producing aggregated kafirin with viscoelastic properties, addition of 83% aqueous isopropanol as a solvent during the extracting of kafirin from dry milled sorghum was required. Thus, in-depth understanding of the isolation procedure could be an important part of research in the near future and a step closer in achieving gluten-like functionality of kafirin for gluten-free bread application. Another area that needs investigation is to probe the understanding of the digestibility of kafirin, as it can be a source of major dietary protein in the developing world.

On the basis of above discussion, it can be seen that zein and kafirin have shown promising outcomes for gluten-free bread development. Zein, in particular, can act as a structural enhancer in combination with hydrocolloids and as a potential cereal protein source in a zein–starch dough system. However, there lies an economic disadvantage of using zein as it is expensive and in future large-scale production of zein is required to set up with spent grain as raw material. Although there are other cereal proteins that may be more suitable from a nutritional point of view, their rheological impact remains to be investigated.

Protein from dairy source

Dairy ingredients have been used for a number of years, and have found numerous applications in the gluten-

free market (Stathopoulos, 2011). Recent work suggests that the application of dairy protein could be an alternative solution for gluten-free product development because of their positive role in improving the nutritional value of the product as well as structure building ingredients. For example, in the case of baked products, protein from dairy sources can strengthen the dough network of batter with improved texture, color, and reduce staling (Arendt et al., 2008a). Dairy proteins are highly functional ingredients and due to their versatility can be readily incorporated into many food products. Milk proteins are highly functional ingredients characterized by a significant nutritional value. They swell in a high level and are able to build up a network (Stathopoulos and O’Kennedy, 2008a, 2008b). Next to the functional benefits, gluten-free products with milk proteins are affluent in calcium and proteins, and, thus, enriched in essential amino acids like lysine, methionine, and tryptophan (Krupa-Kozak et al., 2013). They may be used in bread for both nutritional and functional benefits including flavor and texture enhancement, and storage improvement (Cocup and Sanderson, 1987; Kenny et al., 2001; Mannie and Asp, 1989).

Proteins derived from milk have, in past, demonstrated to improve gluten-free products like breads in terms of preference and increase in the loaf volume as compared with control rice flour bread (Gallagher et al., 2003a, 2003b, 2004). The most extensively used dairy protein in the gluten-free formulation are mainly caseinates (Lazaridou et al., 2007; Stathopoulos and O’Kennedy, 2008a), whey protein concentrate (Lupano, 2003; Sanchez et al., 2004; van Riemsdijk et al., 2011c) and milk protein isolate (Gallagher et al., 2003a, 2004). Use of hydrocolloids along with dairy protein is presently being used as a popular approach for gluten-free product development. At present, mixtures of gums, hydrocolloids, and dairy protein products are the most popular approach (Lazaridou et al., 2007; McCarthy et al., 2005). Caseinates are good emulsifiers and stabilize the batter; isolated and concentrated whey proteins can form gels; high temperature skim milk powder exhibits high water-binding capacity (Stathopoulos and O’Kennedy, 2008b). Although there lies immense possibility of using milk proteins in gluten-free product, there lies some limitation of milk-based protein. For example, an individual suffering from small intestine inflammation due to CD is generally linked to lactose intolerance also (Ortolani and Pastorello, 2006). Secondly, milk proteins can also be the activator of an allergenic reaction (Schober, 2009).

This section aims to discuss the current advancement in context to application of specific dairy protein for development of gluten-free product development.

Whey proteins. They are mainly globular proteins solubilized in the continuous phase of the milk (De Wit, 1990). Whey contains several types of protein at variable concentrations, cumulative mass is about 20% of the total milk protein mass (De Wit, 1998). Whey proteins from dairy sources are considered natural food additives with thickening functionality similar to hydrocolloids, starches, and other thickeners in food systems (Resch and Daubert, 2002). Whey proteins concentrates (WPC) can be used to overcome undesirable weakening of the gluten network in frozen dough products (Asghar et al., 2009). The addition of WPC can modify the rheological properties of the paste of empanadas (traditional meal in Argentina) by increasing the extensibility and decreasing the tenacity of the dough (Lupano, 2003). Apart from its positive role in improving the nutritional value of the product, in the recent years, whey proteins have shown immense possibility as structuring building ingredients for the development of gluten-free products (Krupa-Kozak et al., 2013; Marti et al., 2014; Matos et al., 2014; Thompson, 2009; van Riemsdijk et al., 2011c).

In a recent study, mesostructured whey protein particle system was used in the preparation of gluten-free bread (van Riemsdijk et al., 2011c). The idea of using mesostructure whey protein particle system is based on the hypothesis that the gluten structure present in developed wheat dough features a particle structure on a mesoscopic length scale (100 nm to 100 μ m). Previous studies does support the hypothesis that behavior of the particle suspensions is mainly governed by the mesoscopic properties of the particle networks and the network is strongly elastic at small strain value (Riemsdijk et al., 2010; van Riemsdijk et al., 2011a). This work presents an alternative concept for the design of gluten-free products by the use of whey protein by replacing gluten by whey at mesoscopic scale. Key characteristic of this formulation is that whey protein and locust bean gum are structured into a mesoscopic protein particle suspension. Protein alteration at the mesoscopic scale is relatively a new concept. At this scale, a high degree of interaction is present in the whey protein particle suspension, which can form a particle network. Due to nature of building blocks of food, structuring at the mesoscale is of high interest (Manski et al., 2007). Thus, the use of a mesoscopic whey protein particle network represents an innovative concept to the development of next generation gluten-free products.

The application of whey protein as well as egg albumin as a structure structuring building ingredient was recently investigated for producing gluten-free pasta (Marti et al., 2014). The effects of proteins on the starch-protein interactions and on the overall pasta structure and cooking performance were also

investigated in the study. The ultrastructure of the cooked pasta revealed some discontinuities between protein and starch in pasta sample containing whey protein. This was evident by higher cooking loss of pasta containing whey protein as compared to egg albumin. The addition of whey proteins in the present study increased the surface homogeneity. In conclusion, the study does suggest that incorporation of whey proteins as texturing ingredients can be an interesting approach for producing gluten-free pasta with improved cooking quality without using chemical additives. However, it is suggested that there is a need of optimization of gluten-free pasta in terms of level of whey protein and need to further probe the action of whey protein on gluten-free pasta in future. Moreover, additional research should focus on incorporation of other gluten-free grain with whey protein to understand its effect on ultrastructure, surface textural characteristics cooking behavior of gluten-free pasta.

Addition of whey proteins (5% w/w, flour-protein blend basis), affects the rice flour functionality in terms of pasting properties and rheological properties (Marco and Rosell, 2008c). Rapid viscoanalyzer (RVA) analysis revealed that whey protein and rice prolamins promotes a significant decrease in the peak viscosity as well as final viscosity

The application of transglutaminase (TG) along with the whey protein can be used to develop the protein network and modify the rheological properties of rice dough (Gujral and Rosell, 2004; Marco and Rosell, 2008c). The use of enzyme TG to understand the compatibility between rice flour proteins and different protein in the catalysing crosslinking reaction has been studied in the recent past. In one such study, effect of different protein isolates (pea, soybean, egg albumen, and whey proteins) and TG on rice flour properties was studied (Marco and Rosell, 2008c). The elastic modulus recorded in the oscillatory tests was significantly affected by both the protein isolates and TG. The extent of the effect was dependent on the protein source; pea and soybean proteins increased the elastic modulus, whereas egg albumen and whey protein decreased it.

In one of the studies, it was shown that inclusion of whey protein in gluten-free bread induced a higher volume and decrease in hardness with time (Nunes et al., 2009). The study indicates that the whey protein incorporation improved the nutritional value as well as baking characteristics of gluten-free bread.

Thus considering all the above-mentioned aspects, it can be seen that whey protein offers a significant and interesting approach for development of gluten-free products. Apart from enhancing the nutritive values of the product, it is also seen that it improves the overall quality of different gluten-free products.

Future studies should target on the probing functional relationship between whey protein and development of gluten-free products.

Casein. It is a protein that is found in milk and used independently in many foods as a binding agent (Walstra and Jenness, 1984). It is part of a group called phosphoproteins, collection of proteins containing chemically bound phosphoric acid (Holt, 1997). Proteins, in general, are used as structure building ingredients in solid and semi-solid foods to confer mechanical strength and characteristic textural properties or as thickening agents in fluid foods to enhance the consistency and stability of a product (Chan et al., 2007).

Sodium caseinate addition in the gluten-free formulation besides increase in the nutritive value has been also found to affect the crust and crumb characteristics of gluten-free bread (Gallagher et al., 2003a). It was found that increase in the inclusion levels of the sodium caseinate powder decreased loaf volume, as well as crust lightness and increased the crumb hardness and specific volume and received good acceptability scores in sensory tests. Supplementing the gluten-free formulation with high protein-content dairy powders doubled the protein content of the breads. Thus, there lies possibility of utilization of caseinate in gluten-free formulation with the objective of increasing both nutritional and functional benefits.

Recently, effects of casein along with other additives were studied on the rheological and mechanical properties of non-conventional fresh handmade tagliatelle from amaranth, quinoa, and oat dough (Chillo et al., 2009). The casein incorporation in the range of 0.1–0.3% has a significant effect in terms of rheological properties of the resulting dough. In one of the similar studies on gluten-free rice pasta dough, it was found that guar gum and casein protein supplementation of rice semolina dough resulted in a dough that is easy to handle and process (Sozer, 2009).

Caseinates are widely used for their functional properties, and in the recent study, a production protocol for an aggregated casein-based ingredient fortified with calcium (Ca) was developed (Stathopoulos and O’Kennedy, 2008a). Effect of calcium in concentrated casein systems as a functional replacement for gluten was demonstrated by rheological as well as textural evaluation. Calcium was used in the range of 15–40 mg/g of protein. The authors found that 30 mg Ca/g protein sample was significantly stronger than the sample with different calcium concentration in TPA tests. However, sample under small deformation conditions were significantly different from gluten. Authors concluded that there is a need to further probe the effect of NaCl, an important ingredient in bread making, and

crosslinking enzymes on both the yield and the performance of the casein-based ingredient. Thus, in future it can be expected that under the correct combination of condition, a viable alternative to gluten with textural and rheological properties closely resembling those of gluten is possible.

In the recent research, functionality of proteins (casein) on the rheological and quality properties of rice-based gluten-free muffins was investigated (Matos et al., 2014). It was found that incorporation of casein in rice-based gluten-free muffins increased the specific volume of the muffins. Additionally, the overall results indicated that both the rheological properties of the batters and the technological characteristics of the muffin are dominated by the presence of the type of protein used in the formulations. In general, authors found that the muffins with best visual appearance were those containing casein. Thus, casein can play an important role in the development of sweet-baked gluten-free product. However, additional research has to be focused in future to determine the sensory quality and consumer acceptability.

Protein from legume source

Legumes are one of the most important sources of food proteins. Legumes are a good supplement for cereal-based foods since both legume and cereal proteins are complementary in essential amino acids (Iqbal et al., 2006; Singh and Singh, 1992). Cereals are deficient in the essential amino acid lysine, while legumes have a high content of this amino acid.

Recently, the incorporation of protein from legume source is investigated as an alternative for enhancing the nutritional value of gluten-free bakery products along with improved physical characteristics and overall quality (Gularte et al., 2012; Miñarro et al., 2012). Legume protein isolates or concentrates have gained importance in the food industry because of their high protein contents, and represent an alternative in the development of gluten-free products (Marco and Rosell, 2008b). The successful use of legume protein isolates depends on the versatility of their functional properties, which are influenced by intrinsic factors (composition and conformation of proteins), environmental factors (composition of the model system or food), and methods and conditions of isolation (Chavan et al., 2001; Kim et al., 1990). Apart from their nutritional properties, legume proteins also possess functional properties that play an important role in food formulation and processing (Boye et al., 2010; Roy et al., 2010). In the recent past, the functional properties of legume proteins such as soy protein isolate (SPI) and pea protein isolate (PPI) have been used in the preparation and development of different

gluten-free products. In the recent years, among the different available legumes, soya protein isolate has been exploited widely as a potential ingredient to be used in gluten-free formulation. Soy has long been used to complement grain proteins and to improve nutritional quality by adding necessary amino acids. Further, few report also suggest that it improves mechanical behavior of dough and textural quality of the final bread during storage (Ribotta et al., 2004; Sanchez et al., 2002)

Soy protein isolate. SPI is a highly refined or purified form of soy protein with a minimum protein content of 90% on a moisture-free basis with digestibility of 93–97% (Majzoobi et al., 2013). Additionally, the nutritional value of soy proteins is high; the protein digestibility-corrected amino acid score of SPI is approximately that of egg white. Recent studies indicate that SPI has been a subject of research in the area of gluten-free product development (Marco and Rosell, 2008a, 2008b, 2008c; Matos et al., 2014; Ribotta et al., 2004; Ronda et al., 2011; Ziobro et al., 2013). However, in majority of research, SPI was used in combination with hydrocolloids and results were studied simultaneously. Review of past literature also suggest that incorporation of SPI in rice-based dough influences the rheological characteristics as well as other mechanical properties by increasing the elastic modulus thereby providing the increased elasticity apart from nutritional enhancement (Crockett et al., 2011; Marco and Rosell, 2008c; Matos et al., 2014).

Recently function of different proteins (SPI, PPI, egg white protein (EWP), casein) on the rheological and quality properties of rice-based gluten-free muffins were studied (Matos et al., 2014). Their result indicated that both the rheological properties of the batters and the technological characteristics of the muffin are dominated by the presence of the type of protein used in the formulations. The presence of SPI modified the elastic and viscous component of the rice-based muffins batter, inducing a hardening effect (increase in G' and G'') on the batters. The positive effect of SPI along with other proteins is shown in Figure 4. Few authors earlier reported similar result (Marco and Rosell, 2008b; Ronda et al., 2011). SPI batter showed a progressive increase of G' as the temperature rises, indicating the formation of a more rigid network.

Recent studies have reflected the importance of the SPI in the application of gluten-free bread. Earlier studies in past have suggested that incorporation of SPI have led to an increase in crumb texture and bread volume (Crockett et al., 2011; Sanchez et al., 2002). However, reports also mention the negative influence of soy protein on the gluten-free bread on bread volume (Marco and Rosell, 2008a; Ziobro et al., 2013).

However, it has been reported that the use of hydrocolloid (HPMC) along with the soy protein prevents negative effect of soy protein. Additionally, use of protein isolates in combination with microbial TG has shown promising results with an increase in the protein content and, subsequently, enhancement of the resulting products nutritionally (Kim et al., 2014; Marco and Rosell, 2008c; Moore et al., 2006; Storck et al., 2013).

In one of the recent works, effect of SPI and egg white solids on the physicochemical properties of gluten-free bread was studied (Crockett et al., 2011). The addition of SPI reduced dough stability by suppressing HPMC functionality, reducing available water, weakening HPMC interactions with the starch matrix, and reducing foam stability.

Application of SPI in combination with different starch were used to study rheological properties in cake batter (Ronda et al., 2011). It was found that batters made with rice starch and SPI mixtures 80–20 showed the most similar rheological behavior with respect to wheat flour batters and achieved good quality gluten-free cake. Authors laid importance to the percentage of soy protein to be added in the formulation in order to obtain batters and cakes with optimal characteristics. Thus, incorporation of SPI shows promising path in gluten-free product development.

Carob germ proteins (Caroubin). Carob (*Ceratonia siliqua*), is a leguminous shrub native in the Mediterranean region (Bengoechea et al., 2008; Dakia et al., 2007). Caroubin is a water-insoluble mixed-protein system isolated from carob bean embryo. Caroubin is a mixture of a large number of proteins that are different in size and degree of polymerization, covering a molecular weight range from more than one million to several thousands (Feillet and Roulland, 1998; Rice and Ramstad, 1950; Smith et al., 2010). It has been reported that caroubin, a protein mixture obtained from carob seeds when hydrated, has rheological properties similar to those of gluten (Smith et al., 2012; Wang et al., 2001). Comparative studies of the effects of hydration and temperature on caroubin and gluten with the support of nuclear magnetic resonance, Fourier transform infrared, scanning electron microscopy, and differential scanning calorimetry techniques showed that the caroubin has a more ordered structure than gluten and that hydration has little effect on its secondary structure when compared to gluten. Additionally, on hydration, caroubin, like gluten, forms fibrillar structures and sheets (Wang et al., 2001).

In the recent times, the potential of caroubin protein is used in the improvement of functionality of gluten-free products (Miñarro et al., 2012; Smith et al., 2012; Tsatsaragkou et al., 2012, 2014). In the past also, caroubin have been used in the development wheat-free

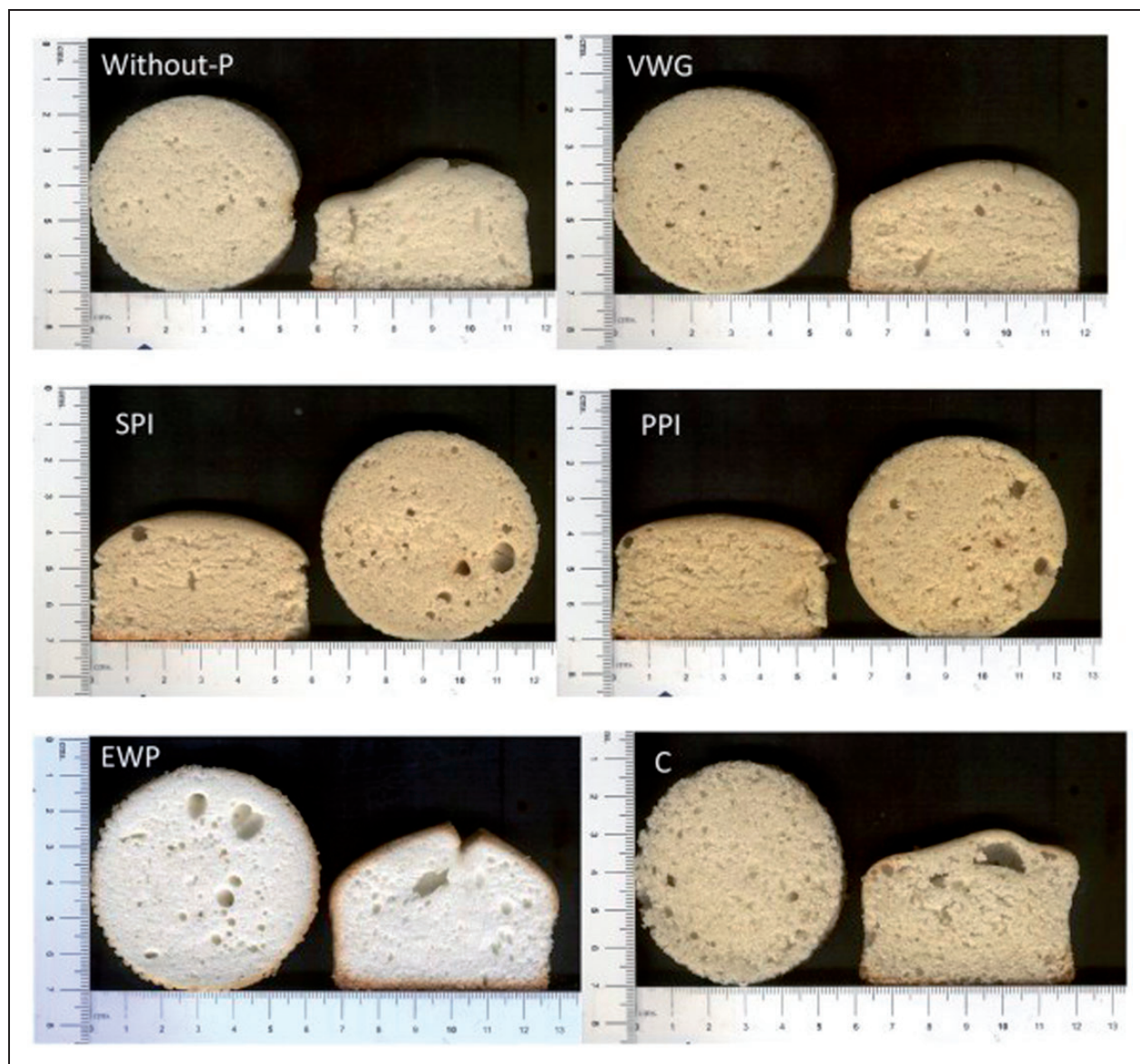


Figure 4. Photographs of cross and longitudinal sections of without protein and with protein white enriched muffins. VWG: vital wheat gluten; SPI: soy protein isolate; PPI: pea protein isolate; EWP: egg protein; C: casein (Matos et al., 2014).

bread (Moritz et al., 1935). Wheat-free breads containing carob germ flour had reduced effects of staling when compared to other gluten-free breads. However, breads made from 30% carob germ flour and 70% maize starch mixtures were dense (specific volumes of ~ 2.5 mL/g) and had high crumb hardness values. This was probably due to the fact that the amount of carob germ flour required to hold gas produced tough dough resulting in lower quality bread. For this reason, it was hypothesized that reducing the amount of carob germ flour while adding a hydrocolloid (HPMC) would soften the dough while allowing greater gas retention. This in turn should result in greater bread quality in terms of specific volume and crumb hardness.

In the recent study, carob germ proteins have been shown to have functional properties similar to wheat gluten enabling formulation and production of yeast leavened gluten-free baked goods from a true dough rather than a stiff batter (Smith et al., 2012). In this work, high quality gluten-free bread was produced by the use of carob germ flour and HPMC with values of crumb hardness and specific volume of gluten-free bread comparable to that of wheat bread.

Addition of carob flour along with rice flour was recently investigated in the development of gluten-free bread (Tsatsaragkou et al., 2012). It was found that, the use of carob flour addition enhanced the protein content of the gluten-free bread with higher quality,

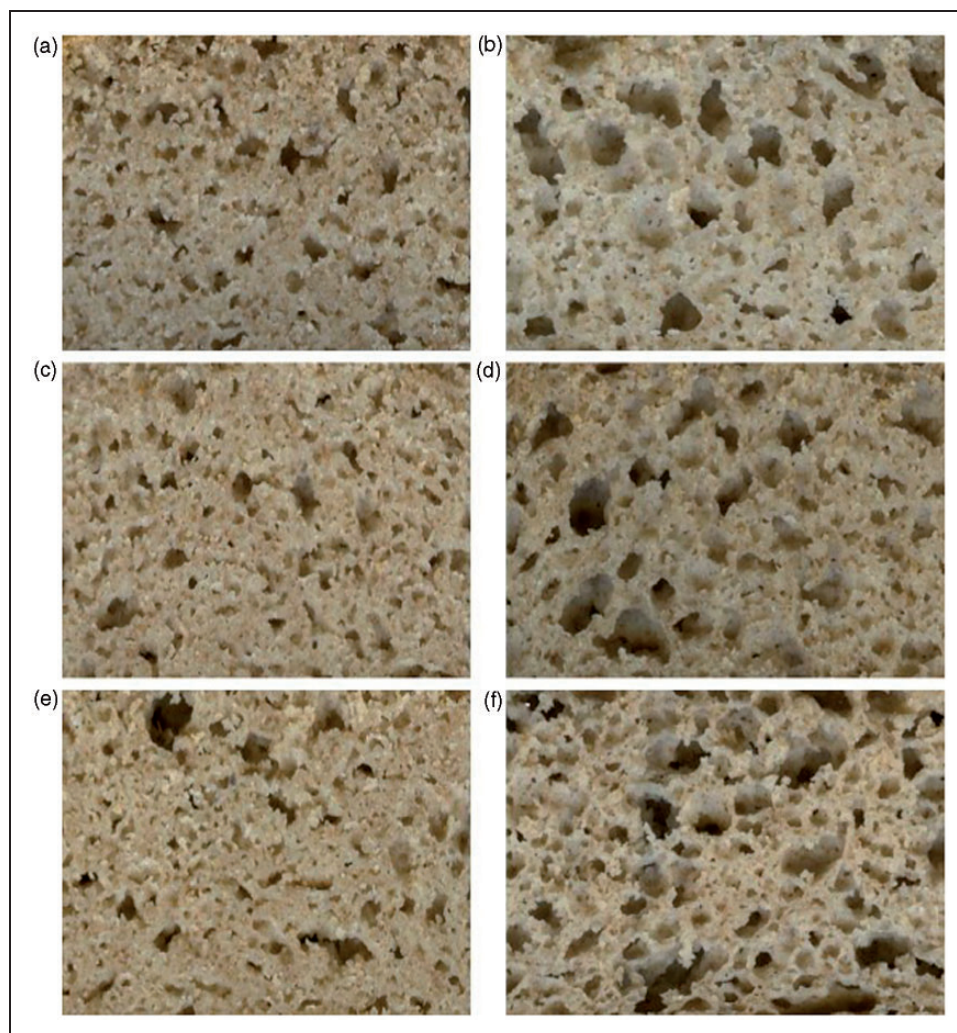


Figure 5. Surface crumb porosity of breads in different carob and water content. From left to right: carob flour/water content 5/80, 5/100 (a, b); 10/90, 10/120 (c, d); 15/100, 15/150 (e, f) (Tsatsaragkou et al., 2012).

in terms of dough proofing, porosity, crumb firmness, and viscoelasticity. However, in this study the role of water in combination with carob flour influenced the gluten-free bread attributes (Figure 5).

Preliminary research showed a great potential for carob germ protein in the use in gluten-free breads (Smith et al., 2012; Tsatsaragkou et al., 2012, 2014). To optimize the quality of products, additional functional ingredients need to be added. These ingredients need to be identified and optimized within a given system. Although there are rheological similarities between caroubin and gluten in the uncooked state, the results obtained here suggest that there may be significant differences between the materials after cooking. More research is needed to understand the structure–function relationships and determine to what extent caroubin might be used as a gluten substitute.

Up to now, there are not many known non-gluten proteins having a tendency to form dough formation

like wheat gluten. In this regard, caroubin proteins unique ability to form protein networks is noteworthy and in future may open new passage for future gluten-free product development.

Egg protein

In the recent years, the incorporation of egg proteins in the development of gluten-free products has been widely used because their proteins are highly functional and can be readily incorporated into the dough (Crockett et al., 2011; Marti et al., 2014; Schoenlechner et al., 2010; Storck et al., 2013; Ziobro et al., 2013). Egg proteins can act as a gluten replacer due to their foaming properties as well as it is known to stabilize crumb structure in bakery products (Kato et al., 1993). For example, egg proteins can promote the dispersion and stabilize the gas bubbles in gluten-free dough systems

(Schober, 2009). Earlier reports suggest that egg proteins in a gluten-free bread system egg proteins forms a viscous film-like continuous protein structure similar to wheat gluten (Moore et al., 2004). Additionally, use of enzyme TG along with egg protein shows a more stable network within a gluten-free bread system (Moore et al., 2006).

In one of the recent works, role of texturing proteins (egg albumen and whey proteins) in the development of gluten-free rice-based pasta in absence of other additives was investigated (Marti et al., 2014). The effects of these proteins (Catassi and Fasano, 2008) on the starch-protein interactions and on the overall pasta structure and cooking performance were also investigated. It was indicated that the use of egg albumen (15%) gave pasta a better appearance, with lower cooking loss, and firmer and nutritionally more valuable as compared to whey proteins. Thus, the work suggests that incorporation of egg albumen as a protein source can be an interesting approach for gluten-free pasta development without the use of any chemical additives. Rheological properties of rice pasta dough were supplemented with proteins (egg white) and gum (Sozer, 2009). It was found that guar gum and protein mixture can be used as a stabilizer together with 50% pre-gelatinized rice semolina. The result shows that incorporation of egg protein along with other results in an improvement in dough properties during gluten-free pasta processing from rice.

In one of the recent studies, functionality of different proteins isolates (soy protein isolate, pea protein isolate, egg white protein, casein (C)) on the rheological and quality properties of rice-based gluten-free muffins was investigated (Matos et al., 2014). It was found that casein and EWP increased the specific volume of the muffins as compared to other protein isolates. Additionally, muffins with best visual appearance were those containing EWP or casein.

The amount of water, albumen, and fat varied in order to evaluate their impact on the textural, structural, and sensory characteristics of the final product (Schoenlechner et al., 2010). Variations in fat amount did not significantly influence any of the response variables investigated. However, the combined addition of fat and albumen resulted in breads that received the best rankings in overall acceptance in sensory evaluation.

Effects of SPI and egg white solids on the physico-chemical properties of gluten-free bread was recently investigated (Crockett et al., 2011). The addition of SPI reduced dough stability by suppressing HPMC functionality, reducing available water, weakening HPMC interactions with the starch matrix and reducing foam stability. At 15% addition, egg white solids became the primary protein scaffolding in the dough

and overcame negative interactions with HPMC, improving the loaf volume.

The effect of protein enrichment (albumin and casein) on characteristics of gluten-free bread was recently studied (Catassi and Fasano, 2008; Storck et al., 2013). The use of TG in combination with egg protein had a positive effect on the specific volume of gluten-free baked product along with the decrease in the crumb hardness. Thus, the use of albumin and casein protein isolates and TG constitutes a promising approach to producing protein-enriched blends for making fermented, gluten-free products.

CONCLUSION

A great part of gluten-free staple products available on the market today are based on starches and do not meet the nutritional requirements. So in future, gluten-free products needs to the fortified using alternative sources of protein. It can be seen that in the recent years, incorporation of alternative non-gluten sources of protein into gluten-free dough has been an interesting approach. Different sources of protein have shown promising results in terms of improving the viscoelastic properties of gluten-free dough and also resulting in improved structure, mouth feel, nutritional quality, and overall acceptability shelf life of these products. However, use of alternative proteins along with hydrocolloids as a structuring agent and enzymes have demonstrated improved structure of gluten-free dough and final product. The next future challenge is to understand the interactions between alternative proteins with other ingredient in the development of gluten-free product.

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REFERENCES

- Alvarez-Jubete L, Arendt EK and Gallagher E. (2010). Nutritive value of pseudocereals and their increasing use as functional gluten-free ingredients. *Trends in Food Science & Technology* 21: 106–113.
- Andersson H, Öhgren C, Johansson D, et al. (2011). Extensional flow, viscoelasticity and baking performance of gluten-free zein-starch doughs supplemented with hydrocolloids. *Food Hydrocolloids* 25: 1587–1595.
- Arendt EK and Dal Bello F. (2008). Functional cereal products for those with gluten intolerance. In: Hamaker BR (ed.) *Technology of Functional Cereal Products*. Cambridge, UK: Woodhead Publishing Limited, pp. 446–475.
- Asghar A, Anjum FM, Allen JC, et al. (2009). Effect of modified whey protein concentrates on empirical and

- fundamental dynamic mechanical properties of frozen dough. *Food Hydrocolloids* 23: 1687–1692.
- Belton PS, Delgadillo I, Halford NG, et al. (2006). Kafirin structure and functionality. *Journal of Cereal Science* 44: 272–286.
- Bengochea C, Romero A, Villanueva A, et al. (2008). Composition and structure of carob (*Ceratonia siliqua* L.) germ proteins. *Food Chemistry* 107: 675–683.
- Blaszczak W, Bonet A and Rosell CM. (2006). Formation of Homopolymers and heteropolymers between wheat flour and several protein sources by transglutaminase-catalyzed cross-linking. *Cereal Chemistry* 83: 655–662.
- Boye J, Zare F and Pletch A. (2010). Pulse proteins: Processing, characterization, functional properties and applications in food and feed. *Food Research International* 43: 414–431.
- Bugusu BA, Campanella O and Hamaker BR. (2001). Improvement of sorghum-wheat composite dough rheological properties and breadmaking quality through zein addition. *Cereal Chemistry* 78: 31–35.
- Catassi C and Fasano A. (2008). Celiac disease. In: Arendt EK and Dal Bello F (eds) *Gluten-free Cereals Products and Beverages*. The Netherlands: Elsevier, pp. 1–22.
- Chan PS-K, Chen J, Ettelaie R, et al. (2007). Study of the shear and extensional rheology of casein, waxy maize starch and their mixtures. *Food Hydrocolloids* 21: 716–725.
- Chavan UD, McKenzie DB and Shahidi F. (2001). Functional properties of protein isolates from beach pea (*Lathyrus maritimus* L.). *Food Chemistry* 74: 177–187.
- Chillo S, Suriano N, Lamacchia C, et al. (2009). Effects of additives on the rheological and mechanical properties of non-conventional fresh handmade tagliatelle. *Journal of Cereal Science* 49: 163–170.
- Crockett R, Ie P and Vodovotz Y. (2011). Effects of soy protein isolate and egg white solids on the physicochemical properties of gluten-free bread. *Food Chemistry* 129: 84–91.
- Dakia PA, Wathelet B and Paquot M. (2007). Isolation and chemical evaluation of carob (*Ceratonia siliqua* L.) seed germ. *Food Chemistry* 102: 1368–1374.
- de Mesa-Stonestreet NJ, Alavi S and Gwirtz J. (2012). Extrusion-enzyme liquefaction as a method for producing sorghum protein concentrates. *Journal of Food Engineering* 108: 365–375.
- De Wit JN. (1990). Thermal stability and functionality of whey proteins. *Journal of Dairy Science* 73: 3602–3612.
- De Wit JN. (1998). Nutritional and functional characteristics of whey proteins in food products. *Journal of Dairy Science* 81: 597–608.
- Durham S. (2010). Defatted corn protein produces palatable gluten-free bread. *Agricultural Research* 58: 28–28.
- Erickson DP, Campanella OH and Hamaker BR. (2012). Functionalizing maize zein in viscoelastic dough systems through fibrous, β -sheet-rich protein networks: An alternative, physicochemical approach to gluten-free bread-making. *Trends in Food Science & Technology* 24: 74–81.
- Fasano A and Catassi C. (2001). Current approaches to diagnosis and treatment of celiac disease: An evolving spectrum. *Gastroenterology* 120: 636–651.
- Feillet P and Roulland TM. (1998). Caroubin: A gluten-like protein isolated from carob bean germ. *Cereal Chemistry* 75: 488–492.
- Fevzioglu M, Hamaker BR and Campanella OH. (2012). Gliadin and zein show similar and improved rheological behavior when mixed with high molecular weight glutenin. *Journal of Cereal Science* 55: 265–271.
- Gallagher E, Gormley TR and Arendt EK. (2003a). Crust and crumb characteristics of gluten free breads. *Journal of Food Engineering* 56: 153–161.
- Gallagher E, Gormley TR and Arendt EK. (2004). Recent advances in the formulation of gluten-free cereal-based products. *Trends in Food Science & Technology* 15: 143–152.
- Gallagher E, Kunkel A, Gormley TR, et al. (2003b). The effect of dairy and rice powder addition on loaf and crumb characteristics, and on shelf life (intermediate and long-term) of gluten-free breads stored in a modified atmosphere. *European Food Research and Technology* 218: 44–48.
- Gianazza E, Viglienghi V, Righetti PG, et al. (1977). Amino acid composition of zein molecular components. *Phytochemistry* 16: 315–317.
- Goodall MA, Campanella OH, Ejeta G, et al. (2012). Grain of high digestible, high lysine (HDHL) sorghum contains kafirins which enhance the protein network of composite dough and bread. *Journal of Cereal Science* 56: 352–357.
- Gujral HS and Rosell CM. (2004). Functionality of rice flour modified with a microbial transglutaminase. *Journal of Cereal Science* 39: 225–230.
- Gularte M, Gómez M and Rosell C. (2012). Impact of legume flours on quality and in vitro digestibility of starch and protein from gluten-free cakes. *Food and Bioprocess Technology* 5: 3142–3150.
- Holt C. (1997). The milk salts and their interaction with casein. In: Fox PF (ed.) *Advanced Dairy Chemistry Volume 3*. New York: Springer, pp. 233–256.
- Iqbal A, Khalil IA, Ateeq N, et al. (2006). Nutritional quality of important food legumes. *Food Chemistry* 97: 331–335.
- Johansson D, Krona A and Stading M. (2012). Influence of surface lipids in commercial zein on microstructure and rheological properties of gluten-free dough. *Annual Transactions of the Nordic Rheology Society* 20: 247–251.
- Kato A, Minaki K and Kobayashi K. (1993). Improvement of emulsifying properties of egg white proteins by the attachment of polysaccharide through Maillard reaction in a dry state. *Journal of Agricultural and Food Chemistry* 41: 540–543.
- Kim SY, Park PSW and Rhee KC. (1990). Functional properties of proteolytic enzyme modified soy protein isolate. *Journal of Agricultural and Food Chemistry* 38: 651–656.
- Kim Y, Kee JI, Lee S, et al. (2014). Quality improvement of rice noodle restructured with rice protein isolate and transglutaminase. *Food Chemistry* 145: 409–416.
- Krupa-Kozak U, Baczek N and Rosell CM. (2013). Application of dairy proteins as technological and nutritional improvers of calcium-supplemented gluten-free bread. *Nutrients* 5: 4503–4520.
- Larkins BA, Lending CR, Wallace JC, et al. (1989). Zein gene expression during maize endosperm development.

- In: Goldberg R (ed.) *The Molecular Basis of Plant Development*. New York: Alan R. Liss, pp. 109–120.
- Lawton JW. (1992b). Viscoelasticity of zein-starch doughs. *Cereal Chemistry* 69: 351–355.
- Lawton JW. (2002). Zein: A history of processing and use. *Cereal Chemistry* 79: 1–18.
- Lazaridou A, Duta D, Papageorgiou M, et al. (2007). Effects of hydrocolloids on dough rheology and bread quality parameters in gluten-free formulations. *Journal of Food Engineering* 79: 1033–1047.
- Lee CC and Mulvaney SJ. (2003). Dynamic viscoelastic and tensile properties of gluten and glutenin gels of common wheats of different strength. *Journal of Agricultural and Food Chemistry* 51: 2317–2327.
- Lupano CE. (2003). Discs for 'Empanadas' with whey protein concentrate. *Journal of Food Technology* 1: 182–186.
- McCarthy DF, Gallagher E, Gormley TR, et al. (2005). Application of response surface methodology in the development of gluten-free bread. *Cereal Chemistry* 82: 609–615.
- Majzoobi M, Ghiasi F, Habibi M, et al. (2013). Influence of soy protein isolate on the quality of batter and sponge cake. *Journal of Food Processing and Preservation*. Epub ahead of print 11 April 2013. DOI: 10.1111/jfpp.12076.
- Manski JM, van der Goot AJ and Boom RM. (2007). Advances in structure formation of anisotropic protein-rich foods through novel processing concepts. *Trends in Food Science & Technology* 18: 546–557.
- Marco C and Rosell C. (2008a). Breadmaking performance of protein enriched, gluten-free breads. *European Food Research and Technology* 227: 1205–1213.
- Marco C and Rosell CM. (2008b). Functional and rheological properties of protein enriched gluten free composite flours. *Journal of Food Engineering* 88: 94–103.
- Marco C and Rosell CM. (2008c). Effect of different protein isolates and transglutaminase on rice flour properties. *Journal of Food Engineering* 84: 132–139.
- Mariani P, Viti MG, Montouri M, et al. (1998). The gluten-free diet: A nutritional risk factor for adolescents with celiac disease? *Journal of Pediatric Gastroenterology and Nutrition* 27: 519–523.
- Marti A, Barbiroli A, Marengo M, et al. (2014). Structuring and texturing gluten-free pasta: egg albumen or whey proteins? *European Food Research and Technology* 238: 217–224.
- Matos ME, Sanz T and Rosell CM. (2014). Establishing the function of proteins on the rheological and quality properties of rice based gluten free muffins. *Food Hydrocolloids* 35: 150–158.
- Matos Segura M and Rosell C. (2011). Chemical composition and starch digestibility of different gluten-free breads. *Plant Foods for Human Nutrition* 66: 224–230.
- Mejia CD, Mauer LJ and Hamaker BR. (2007). Similarities and differences in secondary structure of viscoelastic polymers of maize α -zein and wheat gluten proteins. *Journal of Cereal Science* 45: 353–359.
- Miñarro B, Albanell E, Aguilar N, et al. (2012). Effect of legume flours on baking characteristics of gluten-free bread. *Journal of Cereal Science* 56: 476–481.
- Miyazaki M, Van Hung P, Maeda T, et al. (2006). Recent advances in application of modified starches for bread-making. *Trends in Food Science & Technology* 17: 591–599.
- Moore MM, Heinbockel M, Dockery P, et al. (2006). Network formation in gluten-free bread with application of transglutaminase. *Cereal Chemistry* 83: 28–36.
- Moore MM, Schober TJ, Dockery P, et al. (2004). Textural comparisons of gluten-free and wheat-based doughs, batters, and breads. *Cereal Chemistry Journal* 81: 567–575.
- Moritz B, Ladislaus C and Adalbert S. (1935). Manufacture of mill products for alimentary purposes and of paste goods and baked products from such milled products. Patent 2,025,705, USA.
- Nunes M, Ryan LAM and Arendt E. (2009). Effect of low lactose dairy powder addition on the properties of gluten-free batters and bread quality. *European Food Research and Technology* 229: 31–41.
- Onyango C, Mewa EA, Mutahi AW, et al. (2013). Effect of heat-moisture-treated cassava starch and amaranth malt on the quality of sorghum-cassava-amaranth bread. *African Journal of Food Science* 7: 80–86.
- Oom A, Pettersson A, Taylor JRN, et al. (2008). Rheological properties of kafirin and zein prolamins. *Journal of Cereal Science* 47: 109–116.
- Ortolani C and Pastorello EA. (2006). Food allergies and food intolerances. *Best Practice & Research Clinical Gastroenterology* 20: 467–483.
- Paulis JW and Wall JS. (1979). Distribution and electrophoretic properties of alcohol-soluble proteins in normal and high-lysine sorghums. *Cereal Chemistry* 56: 20–23.
- Pontieri P, Mamone G, De Caro S, et al. (2013). Sorghum, a healthy and gluten-free food for celiac patients as demonstrated by genome, biochemical, and immunochemical analyses. *Journal of Agricultural and Food Chemistry* 61: 2565–2571.
- Resch JJ and Daubert CR. (2002). Rheological and physicochemical properties of derivatized whey protein concentrate powders. *International Journal of Food Properties* 5: 419–434.
- Ribotta PD, Ausar SF, Morcillo MH, et al. (2004). Production of gluten-free bread using soybean flour. *Journal of the Science of Food and Agriculture* 84: 1969–1974.
- Rice A and Ramstad P. (1950). Amino acid compositions of wheat and carob gluten. *Cereal Chemistry* 27: 238–243.
- Riemsdijk L, Sprakel JB, Goot A, et al. (2010). Elastic networks of protein particles. *Food Biophysics* 5: 41–48.
- Ronda F, Oliete B, Gómez M, et al. (2011). Rheological study of layer cake batters made with soybean protein isolate and different starch sources. *Journal of Food Engineering* 102: 272–277.
- Roy F, Boye JI and Simpson BK. (2010). Bioactive proteins and peptides in pulse crops: Pea, chickpea and lentil. *Food Research International* 43: 432–442.
- Rühmkorf C, Rübsam H, Becker T, et al. (2012). Effect of structurally different microbial homoexopolysaccharides on the quality of gluten-free bread. *European Food Research and Technology* 235: 139–146.
- Sanchez H, Osella C and De La Torre M. (2004). Use of response surface methodology to optimize gluten-free

- bread fortified with soy flour and dry milk. *Food Science and Technology International* 10: 5–9.
- Sanchez HD, Osella CA and de la Torre MA. (2002). Optimization of gluten-free bread prepared from corn-starch, rice flour, and cassava starch. *Journal of Food Science* 67: 416–419.
- Schober T. (2009). Manufacture of gluten-free speciality breads and confectionery products. In: Gallagher E (ed.) *Gluten-free Food Science and Technology*. Oxford: Wiley-Blackwell, pp. 130–180.
- Schober T and Bean S. (2009). Potential of prolamins from maize and sorghum to form gluten-like structures in wheat-free bread. *Cereal Foods World* 54: A12.
- Schober TJ, Bean SR and Boyle DL. (2007). Gluten-free sorghum bread improved by sourdough fermentation: biochemical, rheological, and microstructural background. *Journal of Agricultural and Food Chemistry* 55: 5137–5146.
- Schober TJ, Bean SR, Boyle DL, et al. (2008). Improved viscoelastic zein–starch doughs for leavened gluten-free breads: Their rheology and microstructure. *Journal of Cereal Science* 48: 755–767.
- Schober TJ, Bean SR, Tilley M, et al. (2011). Impact of different isolation procedures on the functionality of zein and kafirin. *Journal of Cereal Science* 54: 241–249.
- Schober TJ, Messerschmidt M, Bean SR, et al. (2005). Gluten-free bread from sorghum: Quality differences among hybrids. *Cereal Chemistry* 82: 394–404.
- Schober TJ, Moreau RA, Bean SR, et al. (2010). Removal of surface lipids improves the functionality of commercial zein in viscoelastic zein-starch dough for gluten-free bread-making. *Journal of Cereal Science* 52: 417–425.
- Schoenlechner R, Mandala I, Kiskini A, et al. (2010). Effect of water, albumen and fat on the quality of gluten-free bread containing amaranth. *International Journal of Food Science & Technology* 45: 661–669.
- Shewry PR, Halford NG, Tatham AS, et al. (2003). The high molecular weight subunits of wheat glutenin and their role in determining wheat processing properties. *Advance Food Nutrition Research* 45: 219–302.
- Simpson S and Thompson T. (2012). Nutrition assessment in celiac disease. *Gastrointestinal Endoscopy Clinics of North America* 22: 797–809.
- Singh U and Singh B. (1992). Tropical grain legumes as important human foods. *Economic Botany* 46: 310–321.
- Smith BM, Bean SR, Herald TJ, et al. (2012). Effect of HPMC on the quality of wheat-free bread made from carob germ flour-starch mixtures. *Journal of Food Science* 77: C684–C689.
- Smith BM, Bean SR, Schober TJ, et al. (2010). Composition and molecular weight distribution of carob germ protein fractions. *Journal of Agricultural and Food Chemistry* 58: 7794–7800.
- Smith BM, Bean SR, Selling G, et al. (2014). Role of non-covalent interactions in the production of visco-elastic material from zein. *Food Chemistry* 147: 230–238.
- Sozer N. (2009). Rheological properties of rice pasta dough supplemented with proteins and gums. *Food Hydrocolloids* 23: 849–855.
- Stathopoulos CE. (2011). Dairy-based ingredients. In: Arendt E and Bello FD (eds) *Gluten-free Cereal Products and Beverages*. Burlington, MA: Academic Press, pp. 217–232.
- Stathopoulos CE and O’Kennedy BT. (2008a). The effect of salt on the rheology and texture of a casein based ingredient intended to replace gluten. *Milchwissenschaft - Milk Science International* 63: 430–433.
- Stathopoulos CE and O’Kennedy BT. (2008b). A rheological evaluation of concentrated casein systems as replacement for gluten: Calcium effects. *International Journal of Dairy Technology* 61: 397–402.
- Storck CR, da Rosa Zavareze E, Gularte MA, et al. (2013). Protein enrichment and its effects on gluten-free bread characteristics. *LWT - Food Science and Technology* 53: 346–354.
- Thompson T. (2009). The nutrition quality of gluten free foods. In: Eimear G (ed.) *Gluten-free Food Science and Technology*. New York: John Wiley & Sons, pp. 42–52.
- Thompson T, Dennis M, Higgins LA, et al. (2005). Gluten-free diet survey: Are Americans with coeliac disease consuming recommended amounts of fibre, iron, calcium and grain foods? *Journal of Human Nutrition and Dietetics* 18: 163–169.
- Tsatsaragkou K, Yiannopoulos S, Kontogiorgi A, et al. (2012). Mathematical approach of structural and textural properties of gluten free bread enriched with carob flour. *Journal of Cereal Science* 56: 603–609.
- Tsatsaragkou K, Yiannopoulos S, Kontogiorgi A, et al. (2014). Effect of carob flour addition on the rheological properties of gluten-free breads. *Food and Bioprocess Technology* 7: 868–876.
- van Riemsdijk LE, Pelgrom PJM, van der Goot AJ, et al. (2011a). A novel method to prepare gluten-free dough using a meso-structured whey protein particle system. *Journal of Cereal Science* 53: 133–138.
- van Riemsdijk LE, van der Goot AJ and Hamer RJ. (2011b). The use of whey protein particles in gluten-free bread production, the effect of particle stability. *Food Hydrocolloids* 25: 1744–1750.
- van Riemsdijk LE, van der Goot AJ, Hamer RJ, et al. (2011c). Preparation of gluten-free bread using a meso-structured whey protein particle system. *Journal of Cereal Science* 53: 355–361.
- Walstra P and Jenness R. (1984). *Dairy Chemistry & Physics*. New York: John Wiley & Sons.
- Wang Y, Belton PS, Bridon H, et al. (2001). Physicochemical studies of caroubin: A gluten-like protein. *Journal of Agricultural and Food Chemistry* 49: 3414–3419.
- Witczak M, Korus J, Ziobro R, et al. (2010). The effects of maltodextrins on gluten-free dough and quality of bread. *Journal of Food Engineering* 96: 258–265.
- Ziobro R, Witczak T, Juszczak L, et al. (2013). Supplementation of gluten-free bread with non-gluten proteins. Effect on dough rheological properties and bread characteristic. *Food Hydrocolloids* 32: 213–220.