Title: Wheat gluten: a functional protein still challenging to replace in gluten-free cereal-based foods

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Abstract:

Background and Objectives: Wheat gluten in cereal-based products has unique functionality derived from its viscoelastic properties. Nevertheless, many food applications required its replacement to obtain gluten-free foods but keeping similar quality characteristics. This review analyzes the distinctive characteristics of wheat gluten, and the technological strategies implemented to mimic its behavior within the gluten-free systems.

Findings: The viscoelastic behavior of wheat gluten is due to the interplay of glutenins and gliadins after being hydrated and subjected to mechanical stress. Disulfide bonds and non-covalent interactions are key in holding its structure and explaining its solubility and hydrophobicity. Gluten-free flours and starches have represented the first adopted strategies for gluten replacement, but results have not been completely satisfactory. To tackle this issue, non-wheat protein addition, physical treatments, hydrocolloids, enzymes, and emulsifiers have allowed to recreate a pseudo gluten network of the cereal-based foods.

Conclusions: Despite technological sensorial achievements, a gap still exists when gluten-free products are compared with their wheat-based counterparts. A better comprehension about the coactions of different processing aids and technologies could offer future answers.

Significance and Novelty: The review points out the main characteristics of the wheat gluten uniqueness, shedding light on its replacement strategies to guide future research.

Keywords: wheat, starch, protein, gluten-free, hydrocolloids, enzymes

1. Introduction

Going from spelt, mainly consumed during the Bronze Age, to the modern baked and extruded goods of nowadays, wheat has always been a staple of mankind's diets over the millennia (Bell, 1987). But it was not until the mid-eighteenth century that by kneading a wheat dough under water, Jacopo Beccari observed the presence of a viscoelastic matter after starch had flowed away. In doing so, the Italian chemist discovered the wheat gluten (WG) (Beccari, 1745). Since then, much research has progressed with the aim of explaining and clearing up the contribution of gluten to the final quality of the wheat-based products. In parallel, a quick look at the search interest relative to the word "gluten free" in Google (June 2022) during the last fourteen years, confirms its great popularity (Google Trends, 2022). That reveals the increasing interest in finding gluten substitutes that would imitate its role within the food matrices and optimizing process strategies to create WG-like structures. During the last two decades, new unconventional GF flours, physical processes and processing aids have been explored with the goal of getting as close as possible to the WG-containing products, especially in terms of texture and sensory features. Owing to that, much scientific knowledge has been generated regarding the WG and its potential substitutes, while the grocery stores shelves have been filled with new GF products. This review analyzes the distinctive characteristics of WG, and the technological strategies implemented to mimic its behavior within the GF systems.

2. Wheat gluten performance in the main food technologies

2.1 Wheat gluten chemistry

Gluten has been the focus of many researchers trying to understand its unique physical properties. Focusing on the protein content of wheat (*Triticum aestivum*), around 70-80% represent the storage proteins (Wieser et al., 2022), that when subjected to hydration and mechanical energy give rise to the WG. They contain high number of non-polar amino acids and glutamine residues with a high hydrogen-bonding potential, and low content of charged side groups, which explain their poor solubility in water or dilute salt solution (Veraverbeke & Delcour, 2002). WG has been separated by sodium dodecyl sulfate-polyacrylamide gel electrophoresis into two main fractions, monomeric gliadins and glutenins, which have higher molecular weight (MacRitchie et al., 1990; Kasarda, 1989). Fractions from the first group are soluble in alcohol-water solutions (60% ethanol) while, the second ones have proven more hydrophobicity (Schmid et al., 2016). In a dough-system, gliadins provide viscosity and extensibility, whereas strength and elasticity are dependent on glutenins. WG could be seen as “two-components glue” in which gliadins act as plasticizer for glutenins (Wieser, 2007). The functionality of this protein depends on the balance of these two components. Cysteine residues are pivotal for the creation of a three-dimensional structure (Grosch & Wieser, 1999; Shewry & Tatham, 1997). In fact, they can be found as free sulfhydryl or can participate in the formation of disulfide bonds within the same polypeptide (intra-chain disulfide bonds) or between different polypeptides (inter-chain disulfide bonds) (Fig.1) (Shewry et al., 1986). Additional covalent bonds (tyrosine-tyrosine crosslinks) between WG protein and tyrosine-dehydroferulic acid of arabinoxylans contribute to the WG network formation (Tilley et al., 2001; Piber & Koehler, 2005). Non-covalent bonds, such as hydrogen bonds, ionic bonds, hydrophobic bonds also contribute to the structure (Wieser, 2007). Large consensus has been obtained by the “loop and train” model proposed by Belton (1999) (Fig.1). According to the author, the glutenin elasticity is mainly caused by hydrogen bonds occurring between and within its chains. Specifically, protein-protein interactions (interchain hydrogen bonding) are considered trains, while loops are referred to some zones generated by the hydrogen bonds between water and glutamine. With the hydration increase, more loops regions are developed. The application of low extension produces a double effect, firstly it stretches the loops out and after unpacks the trains zone. When additional extension is applied, protein-protein interactions increase, chains become stiffer, and loops disappear (Belton, 1999). After removing the extension, polymer relaxes and loops can be formed again (Jekle & Becker, 2015).

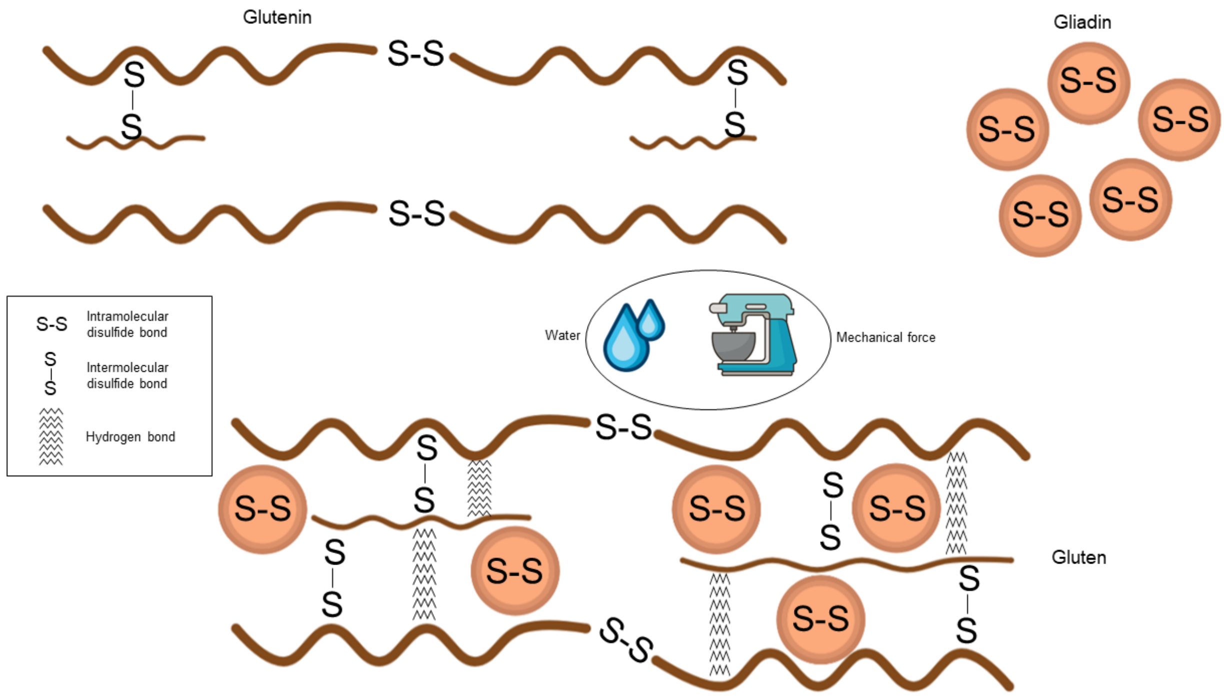

Fig. 1. The development of gluten network according to Shewry et al. (1986), Belton (1999) and Veraverbeke & Delcour (2002).

2.2 Wheat gluten in breadmaking

Bread loaves with high volume and well-defined aerated crumb always embody the gold standard in terms of product acceptability. Apart from starch, which leads a key role in crumb formation, WG network is required, throughout the process, to ensure the creation of the desired product. To increase the interactions between proteins, WG polymers must be in their rubber-like state (above their glass transition temperature). Usually, glass transition temperature is reduced with the moisture content increase (Toufeili & Kokini, 2004). At room conditions, dry WG (moisture content < 20%) is on its glassy state below its glass transition temperature; as hydration increases, WG gets fully hydrated (moisture content > 35%), assuming the typical aspect of a rubbery viscoelastic mass (Toufeili et al., 2002). In operating circumstances, precisely during mixing and kneading, water acts as plasticizer, increasing the interaction rate among WG chains, while shear contributes to give strength to the dough system. In fact, some studies have highlighted the importance of different parameters, such as mixing time, speed and quantity of applied mechanical energy for the ideal development degree of the WG network (Baudouin et al., 2020). Because of that, during dough formation, over-mixing conditions would cause a disulfide bond breaking with losses in elasticity, whereas poorly developed WG network with sticky dough would occur in under-mixing conditions. During proofing step, tiny air pockets, already formed during the mixing stage, become filled with carbon dioxide produced by the yeasts. The continuous bubble size growth reduces the thickness of their starch-WG walls, generating coalescence phenomena (Hayman et al., 1998). Uncontrolled bubble volume increase would lead to a loss of gas retention with consequent reduced volume and coarse crumb after baking (Grenier et al., 2021). Above 60°C, water loss, WG denaturation and especially the heat-induced crosslinking contribute to make stiffer the network until its rupture, occurring at normal baking temperatures (Rosell et al., 2013). Unquestionably, WG is fundamental for baking performances of wheat flours and any action on WG has direct impact on doughs. A good balance between elasticity and viscosity is of primary importance to allow higher gas retentions and breads with more attractive features (Fig. 2).

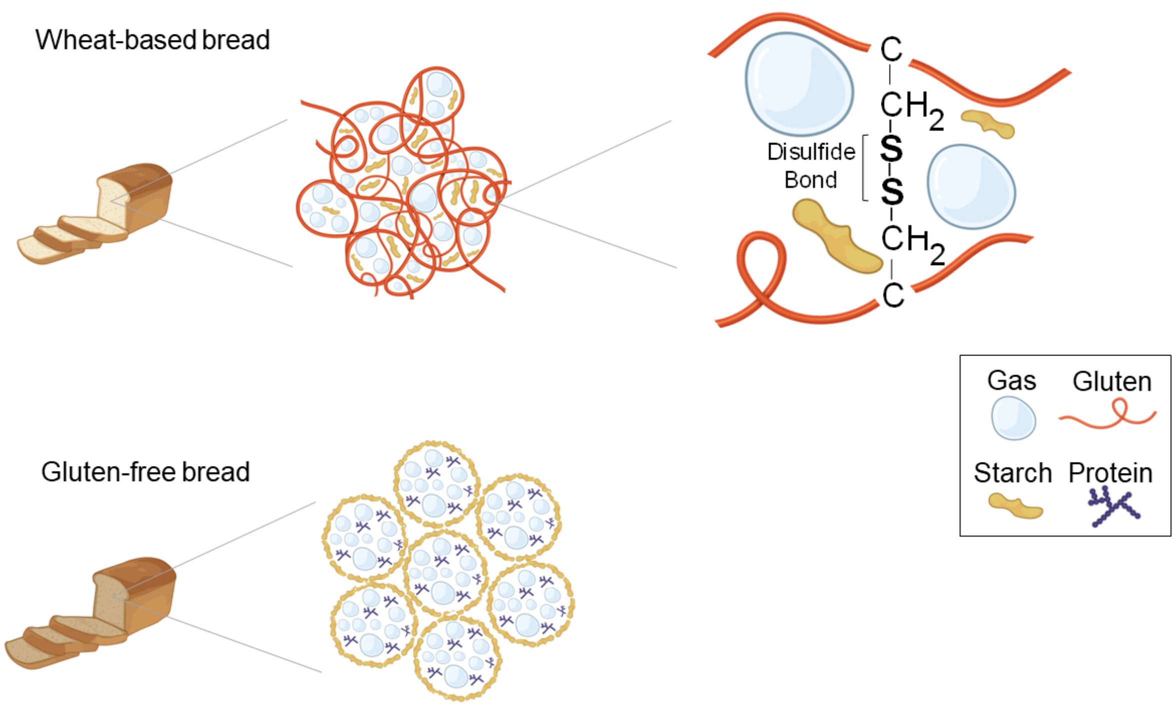

Fig. 2. Structural differences between wheat-based and gluten-free breads

2.3 Wheat gluten in pasta and noodles making

A high visco-elasticity network is essential for the optimal development of pasta and noodleswith superior quality. Usually, products with high firmness, lack of stickiness and minimal cooking solid losses are guaranteed by the presence of a strong WG network. Pasta manufacturing involves the use of durum wheat semolina and water that are subjected to various steps such as, hydration, mixing, forming, and drying before the home cooking (Pagani et al., 1986). Extrusion cooking is the main technology utilized by the food industry to produce the major types of dried pasta. Following the water addition, kneading and extrusion, starch becomes increasingly hydrated while WG starts unfolding. In these stages, hydrated WG mass is stabilized by weak hydrogen, ionic, as well as hydrophobic bonds, forming a continuous network that enclose the starch granules (Guerrero et al., 2014). Usually, during these steps, temperature is kept below 50°C as a way of protecting WG and starch from any heating-related damage. Notably, disulfide/sulfhydryl exchange reactions occur at temperatures beyond 55°C for glutenins and 70°C for gliadins. These phenomena take place mostly during the drying steps, in which WG network is reticulated (protein solubilization) resulting pivotal in limiting starch swelling throughout the next cooking stage (Lamacchia et al., 2007). Martin et al. (2019) highlighted the role of high temperatures during drying, promoting higher number of covalent bonds that improve the cooking performance of the pasta. During this last stage, managed by the final consumer, a strong water competition between starch and protein occurs (Cubadda et al., 2007) (Fig. 3). Boiling water allows starch gelatinization and WG coagulation, and higher pasta firmness is obtained when protein interactions prevail over the starch gelatinization. By doing so, WG network traps the starch granules, preventing their spill and the associated final adhesiveness.

The importance of a fully developed and visco-elastic WG network in pasta goods is also reflected in noodles making. In fact, Yao et al. (2020) reported that the hardness of wheat starch-based sheeted noodles improved after wheat WG addition (14%). Definitively, by controlling starch swelling and gelatinization along with the formation of a strong network, WG is of a great significance in pasta and noodles manufacturing, helping to prevent solids release during cooking and sticky texture in the end-products (Fig. 3).

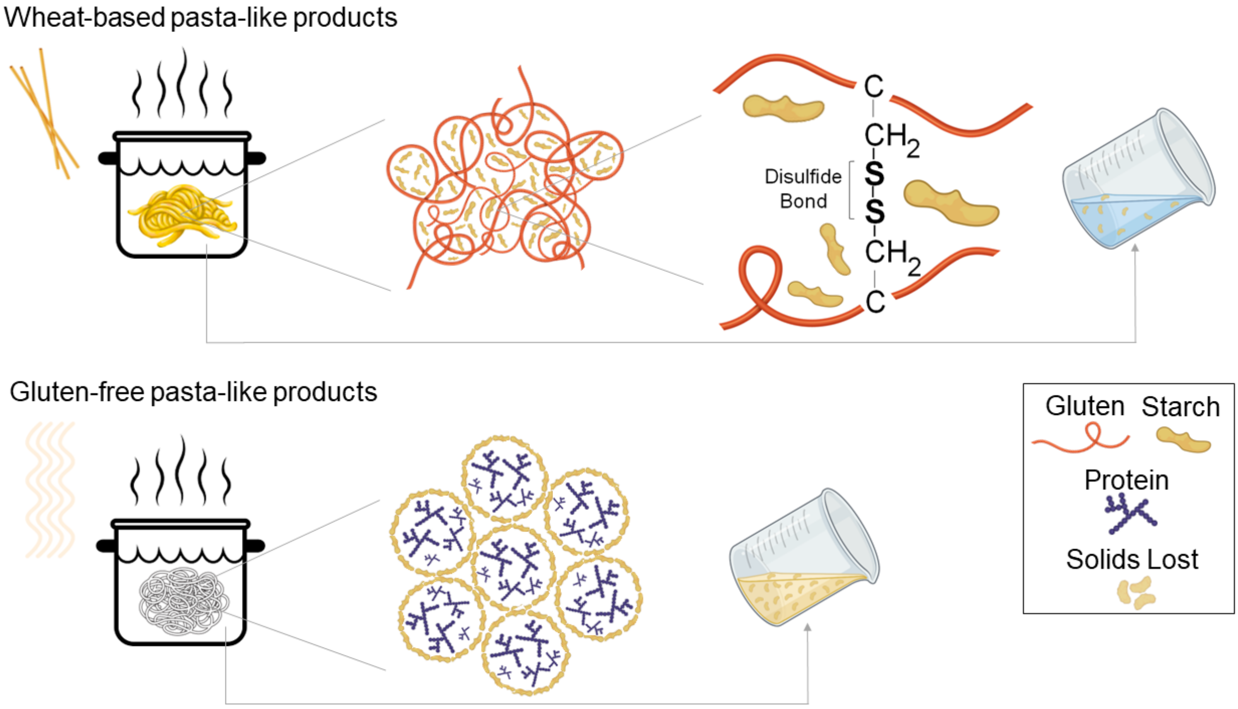

Fig. 3. Structural differences between wheat-based and gluten-free pasta-like products.

3. Strategies for wheat gluten replacement

In the previous sections, the importance of WG in guaranteeing certain technological characteristics has been pointed out. The necessity of producing GF foods has prompted much effort both in academia and food industry. Different strategies have been reported during the last thirty years with the main purpose of substituting WG to create GF food products with similar characteristics of those wheat-based ones. In fact, using "gluten replacement" or "gluten substitution" as retrieval keywords in the Food Science Technology category of Web of Science™ scientific database, five hundred ninety-five documents came up from 1991 to 2021. Keywords co-occurrence network displayed by Fig. 4 was obtained through VOSviewer version 1.6.18 after picking the first one hundred keywords with an occurrence frequency greater than eight. The analysis of the keywords found in the retrieved publications offers a valid aid, as well as its graphical representation in the form of co-occurrence network (Fig. 4). This extension of word counting allows to know the most significant research terms, the configuration of the topics examined, the focus quantified by the number of occurrences (size of nodes), while each color represent a different cluster. Five distinct clusters were found, the first one containing twenty-five items (red color) focused on physicochemical properties of GF products, especially on the digestibility of GF pasta-like products. The second cluster included twenty-one items (green color) and defined the role of the starch in GF breadmaking. Twenty-one items were gathered by the third cluster (blue color), which was basically related to the quality, texture and the role of dietary fiber within the GF foods. Identified by the yellow color, nineteen items were in the fourth cluster regarding the rheological properties and the processing aids used in GF food technology. Lastly, the fifth cluster (purple color) embraced fourteen items mainly concerning dough, frozen dough, steamed bread, and baking properties. In view of that, a description of the most studied strategies, put in place to imitate the WG behavior within the food matrices, will be addressed in the following sections.

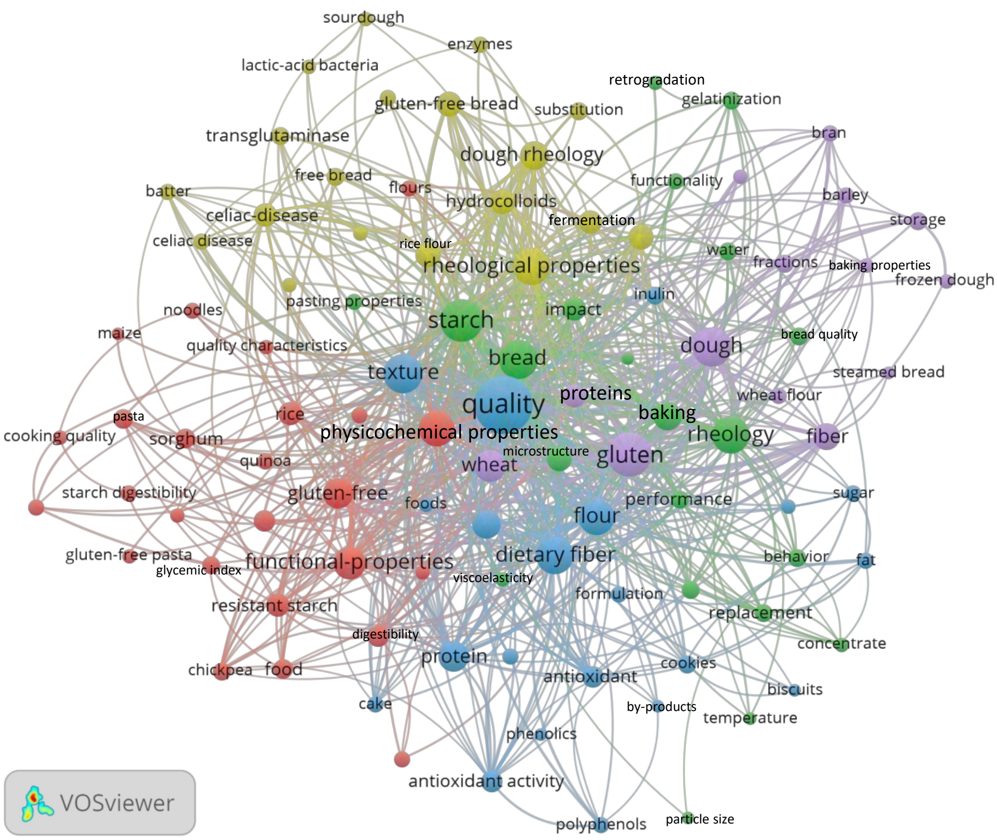

Fig. 4. Keywords co-occurrence map of "gluten replacement" or "gluten substitution" in Web of Science^{TM}.

3.1 Gluten-free flours and starches

To tackle the rising demand for GF product, naturally GF flours was one of the early approaches and extensive literature has been published proposing different GF recipes. Only fundamental concepts have been selected in relation with the functional replacement of gluten. Rice, maize, soy, pulses and pseudocereals have constituted the main raw materials for bakery and pasta-like GF products. Particle size of the flours is crucial for GF breadmaking. According to De la Hera et al. (2013), GF breads made with coarser maize flours (up to 106 μm) had higher volumes, whereas finer flours (<106 μm) showed lower dough development capacity; authors also reported that G''/G' was positively correlated with starch content and negatively with protein. Despite the existence of that correlation, no fundamental studies have been pursued to explore the chemistry and functionality of those flours' proteins and how to improve it. The potential role of the hydrophobicity and hydrophilicity of those proteins have been pointed out (Renzetti, & Arendt, 2009; Renzetti & Rosell, 2016), but other properties like glass transition temperature and the extent of energy contribution in creating a network remain unexplored. Considering the existing knowledge about gluten proteins interactions, focus on other plant-based proteins, and to promote protein-protein interactions besides their performance when physical constraints (energy strain, temperature, pH) have been neglected. Oftentimes, blending GF flours with starches ensures higher volume and better texture to GF breads (Roman et al., 2019), as well as improved firmness to GF pasta-like products (Gao et al., 2018). In flours, their larger and more compact particles kept the integrity during kneading, resulting more resistant to the mechanical stress and producing lower expansion. From the other hand, the lower consistency but higher gas holding capacity and volume expansion observed in starch-based GF breads are related with their different morphology, water absorption capacity and pasting temperature that determine the interaction of the starch granules within the matrix (Martínez & Gómez, 2017). Similarly, GF pasta-like products have extensively adopted starches, utilizing the knowledge based on some oriental practices for starch noodles making.

In GF breadmaking, the amylose content of the flour has been an issue for debate. Baking performances of GF breads made from long-grain rice flours were influenced mostly by water binding capacity, swelling power, swelling volume and thermal properties like gelatinization temperature (Cornejo & Rosell, 2015). From the other hand, Yano et al. (2020) remarked that the expansion ratio of rice flour-based GF breads was amylose content-dependent; the greater amylose content the better expansion, as well as batter viscosity and the maintenance of its foamy structure during proofing. In GF pasta-making, high-amylose rice varieties are sought, because of their better structuring properties that guarantee superior performances during cooking (Marti & Pagani, 2013). In fact, amylose chains limit the swelling of granules during heating, promoting molecular reassociation upon cooling. Some authors stressed the role of amylose in gel formation; in fact, significant positive correlations were found between gel (formed at 95-140°C), hardness and amylose content in starches from maize, potato and pea (Liu et al., 2019). Indeed, the capacity of high amylose starches in reassociating with each other and forming harder gels, seems to be key for a development of stronger network that reduce cooking loss and help to achieve GF pasta-like products with higher firmness.

Also the role of naturally present lipids in pseudocereal's flours have been pointed out for their role in the gas cell stabilization before the starch gelatinization or even the protein aggregation upon heating that could create stronger protein network (Alvarez-Jubete et al., 2009). Likewise, amino acids composition of pulse flours has been related to the high foam expansion and stability, and in consequence high bread volume and crumb softness obtained with chickpea flour (10%) blended with rice flours and starches (maize and cassava) (Collar et al., 2015). Presumably, amino acids contained in chickpea might form an interfacial layer that keep the air bubble in suspension with a consequent formation of a well-defined structure (Miñarro et al., 2012).

By summing up, GF matrix with lower consistency have been produced to hold a significant amount of carbon dioxide during proofing and to achieve higher volumes loaves, as opposed to certain GF pasta-like products, in which stronger structure with high capacity to retrograde is needed to assure better performances during cooking and final firmer textures. Research has been focused on flours properties and their starch functionality, assigning to starch the structuring role in the GF dough/batter. Structure, amylopectin/amylose ratio and granules morphology of starch are pivotal in determining water absorption and pasting behavior, which underlie the rheological properties. However, additional knowledge about the nature of the proteins in gluten free flours would allow defining the process conditions that could promote proteins interactions and viscoelastic properties. Currently the same GF breadmaking conditions are applied independently on the flours origin and their composition, but likely the distinctive characteristics of their constituents could show different performance under adapted process settings. More knowledge about the interactions among proteins and starch chains, and other macromolecules in GF system, as well as the influence of temperature, pressure, pH and ionic concentration is needed to clarify the relationship between process conditions, ingredients and final product quality.

3.2 Non-wheat proteins

Initially, the inclusion of proteins in GF foods was studied solely for nutritional enrichment purposes, and only later on its functionality as network forming agent was considered (Horstmann et al., 2017). Non-gluten proteins functionality has been tested in rice flour-based cake batters observing lower density and higher viscosity after the addition of pea protein concentrate, egg white powder and whey protein isolate (15, 30 and 45%). Both animal proteins incorporation dramatically increased hardness and final volume, while the vegetables ones reduced the cohesiveness (Sahagún et al., 2018). Egg white and casein proteins (13%) led to rice based batters with a stronger network. Likely, due to their capacity in reducing surface tension, better stabilization of the foam at gas-liquid interface is attained, retaining more air within the structure of rice flour GF muffins (Matos et al., 2014).

In the GF pasta field, liquid egg albumen (15%), replacing rice flour, originated a stronger network, stabilized by hydrophobic interactions and disulfide bonds that was accountable for the better appearance and texture of the final GF macaroni (Marti et al., 2014). Encouraging results were reported after the incorporation of rice protein concentrate (up to 10%) for rice flour spaghetti manufacture, in particular cooking time, cooking loss and firmness were reduced while stickiness increased. However, the cooking performances and the textural features, as well as the overall acceptability of the GF samples were quite far from that of wheat control (Detchewa et al., 2022).

Soybean protein has been widely utilized in many food applications because of their well-known emulsification, foaming, gelation, and water-fat absorption properties. These qualities are favored by its two major protein fractions, glycinin (11S globulin) and β-conglycinin (7S globulin). The first one enable to develop harder gels owing to its higher content of thiols groups. The second one, β-conglycinin, has more foldable structure and higher hydrophobicity and emulsifying ability (Fukushima, 2011), which makes it potentially useful for GF breadmaking. In fact, no significant differences were reported about the textural properties of rice flour-based GF breads containing 10% of vital WG and those made with β-conglycinin (10%) (Espinosa-Ramirez et al., 2018). Scanning Electron Microscope micrographs remarked the similarities of both protein enriched matrices; but β-conglycinin samples were characterized by a higher number of larger pores and thinner lamellae, confirming its suitability in strengthening the protein-starch network for a better carbon dioxide holding during proofing and baking (Espinosa-Ramirez et al., 2018).

Overall, the addition of different protein fractions can be a valid approach for the technological challenge of recreating the WG network, particularly after their isolation and characterization as it has been done with soybean proteins. Stabilization of the protein network (mostly via hydrophobic interactions and disulfide bonds) allows improving the cooking performance of GF pasta-like products and increase the gas hold retention in GF bread making. This is acceptable when the comparison is made with samples solely prepared by GF flours, but when it moves towards wheat-based models, the quality gap is still in there. The WG polymerization mechanism has been widely discussed but regarding non-wheat proteins, very little has been made so far. The understanding of their amino acid composition, identifying those sulfur-rich that have proven to be pivotal in the creation of disulfide bonds, could give more valuable information for the understanding of the network creation. By simulating the main process conditions, the study of the protein structure changes and the different interactions among the different protein chains with starch and lipids could give more insights about the key points and limiting factors involved in the creation of a pseudo-WG network.

3.3 Physical treatments

The important role of starch in GF food matrices is driven primarily by its functional changes occurring during food products processing. In fact, in its native state, starch is insoluble in water, while in excess of water, and under heating conditions it swells and gelatinizes giving viscosity and then retrogrades during the cooling stage. Physical treatments of GF flours and starches have been implemented for technological purposes to bring GF products closer to those WG containing. Heating, pre-gelatinization, annealing and high-moisture treatment have been the most explored ones (Iuga & Mironeasa, 2020). Starch is the principal target of these types of treatments that, by changing its native structure, promote interactions between the chains, generating end-products with changed features in terms of crystallinity, water absorption capacity and pasting properties (Shi et al., 2018). Heating starch suspension above the onset temperature represents the key step in the pre-gelatinization treatment. For instance, the incorporation of 30% of pre-gelatinized maize flour followed by sheeting provides stronger and more cohesive dough but with low extensibility (Khuzwayo et al., 2020). GF breads with lower crumb hardness and chewiness were obtained from doughs with low elasticity and improved resistance to deformation after adding pre-gelatinized cassava starch (10%) to jasmine rice flour (Pongjaruvat et al., 2014). Nevertheless, by blending pre-gelatinized *Colocasia* spp. Cormels' flour (50%) with its raw counterpart caused higher losses during baking and the final GF breads showed lower expansion with higher, hardness, cohesiveness, chewiness, resilience, and springiness (Calle et al., 2020). Therefore, despite knowing starch gelatinization process, differences among starch sources make necessary adapted treatments and processes, which have not sufficiently explored.

Concerning GF pasta making, pre-gelatinizing GF flours is the most common process currently adopted by the manufacturers because of it does not require major changes in the production process and the same press before extrusion could be used. Yalcin & Basman (2008) reported the effect of the pre-gelatinization in rice noodles also highlighting the importance of the gelatinization level; in fact, lower cooking losses and better sensory properties were found in samples with a 25% of gelatinization level as opposed to those with 15, 20 and 30%, respectively. The application of heating above the glass transition temperature but below the gelatinization one usually applies to heat moisture treatment in low-moisture condition (≤ 35% w/w) and annealing in intermediate/excess of water content (from 40 up to 65%) (Jacobs & Delcour, 1998). Treated glutinous rice flour at 90°C for 30 min at powder to water ratio of 3:7 (w:w) was employed for GF noodles production; dough resulted softer and more extensible, while the final samples showed very fragile structure compared to those made from wheat flour (Cai et al., 2016). For the technological improvement of GF breads, rice and corn slurries, previously gelatinized, have been successfully used as improver, obtaining GF breads with higher volume, less chewiness and softer crumb (Bourekoua et al., 2016).

As part of physical treatments, low-pressure homogenization has recently been applied with interesting results in GF breadmaking. Boulemkahel et al. (2022) reported that long/medium grain rice flours showed reduced particle size and an increased content of damaged starch after being homogenized at low pressure (30 MPa, 3 passes). The higher level of damaged starch might have contributed to increase the gas production during proofing with consequent higher specific volume of the samples after baking; moreover, lower hardness, as well as higher cohesiveness and resilience were found in the GF breads after the incorporation of the homogenized flours.

The aforementioned physical treatments, as well as others like cold plasma, microwave, electric pulses, extrusion and so on, can contribute to the improvement of GF breads and pasta-like products, but more efficient process must be developed to avoid that energy requirements for these technologies limit their applicability. As a future step, physical treatments could be valuable allies to favor green labelling in GF food products, making the ingredient lists shorter. However, more insights are needed to characterize the microstructure changes of the food biopolymers, so as to identify the most effective physical treatment to apply.

3.4 Hydrocolloids and gums

This category probably encompasses the most utilized processing aids in GF formulations. Hydrocolloids are a macro group of different water-soluble polysaccharides with several chemical structure that determine their functional properties (Zoghi et al., 2021). The functionality of these macromolecules can vary depending on the temperature of the system in which they are acting (Mir et al., 2016). For instance, carboxymethylcellulose, guar and xanthan gums are soluble in cold water, whereas carrageenan, locust bean gum and various alginates exert their action in hot water (Mir et al., 2016). The ability to hold water of those hydrocolloids/gums competing with the starches during gelatinization and their interactions with them might be responsible of the results obtained with the extensive number of scientific papers describing specific recipes containing hydrocolloids (McCarthy et al., 2005; Rosell et al., 2001; Padalino et al., 2013). Through their hydrophilic long-chains molecules, hydrocolloids can control the rheology of aqueous systems; specifically, they firstly interact with water molecules via hydrogen bonds, incorporating them in the inter-molecular or intra-molecular voids of their three-dimensional structure (Salehi, 2019). GF formulations require higher amount of water to develop an essential viscosity, as opposed to their wheat-based counterparts that need less water, however, their effect is greatly dependent on the pair of starch/flour and the specific hydrocolloid (Rosell et al., 2011). In this regard, Morreale et al. (2018) pointed out the key role of hydration level (90, 100 and 110%) in defining the viscoelastic behavior of GF batter based on rice flour and hydroxypropylmethylcellulose (1, 2 and 3%) with different viscosities. According to findings, GF breads with better texture features were obtained by adding 2% of high viscosity HPMC

(15,000 mPa.s) and applying a hydration of 110%. In GF noodles based on tiger nut powder, hydrocolloids type (xanthan gum, guar gum and carboxymethylcellulose) and hydration level (constant and adjusted on the mix requirement) significantly affected dough thermomechanical properties, cooking performances and final texture. Samples with adapted hydration (24%) and xanthan gum (0.5% w/w) showed the lowest value of cooking loss and higher firmness (Gasparre & Rosell, 2019). Nevertheless, in fermented rice noodles, xanthan gum incorporation (up to 0.1%) did not show any significant effect in terms of final firmness, as compared with guar gum (up to 0.1%) samples that obtained the highest values (Srikaeo et al., 2018).

The development of a three-dimensional structure, which ensures GF end-products with higher quality is attributable to the structure of the hydrocolloids. In this framework, the high presence of hydroxyl groups promises more interaction via hydrogen bonds with water molecules, giving to the GF system an increased capability of binding water. In practice the result is an enhancement of the structure viscosity, which is also involved in reducing phase separation and keeping the foamy formation entire. Still, the complete comprehension of their structures, their higher water requirements, the interactions between them and different raw materials, as well as the role of certain processing variables are worthy of further elucidations.

3.5 Enzymes

Different enzymes, promoting linkages within proteins, have been considered for the creation of a three-dimensional network as close as possible to that WG-based. Remarkable results have been reported about the effect of some cross-linking enzymes, such as glucose oxidase (indirect cross-linking) and transglutaminases (direct cross-linking). After the conversion of glucose to gluconic acid operated by the glucose oxidase, the generated hydrogen peroxide interacts with the thiol groups of the WG, with consequent creation of more disulfide bonds and gelation of water-soluble pentosans that modify the rheology of the dough system (Gujral & Rosell, 2004a; Ebling et al., 2022). This tendency was also described when rice flour was used for GF breadmaking, in fact, the addition of glucose oxidase (up to 0.03%) caused a decrease of the free sulfhydryl groups (Gujral & Rosell, 2004a). This reduction reflected the development of new disulfide bonds that improved the dough consistency, the elastic and viscous moduli, creating samples with greater volumes (Gujral & Rosell, 2004a). By catalyzing the cross-linking between glutamine and lysine protein residues, transglutaminase is accountable for the formation of valuable protein network within the GF matrices (Moore et al., 2006; Marco et al., 2008). Increasing quantities of transglutaminase (0.5, 1.0 or 1.5% w/w) improve viscous (G'') and elastic (G') moduli of GF rice flour batter; and 1% of transglutaminase provides the highest bread volume and softest crumb (Gujral & Rosell, 2004b). Same increase of G'' and G' was reported by Kim et al. (2014) after the addition of 1% (w/w) of transglutaminase to rice flour alone or blended to 10% (w/w) of rice protein isolate for the GF sheeted noodles. However, GF fava bean pasta treated with transglutaminase (20 nkat/g flour dm) showed higher cooking loss and reduced water absorption compared to durum wheat semolina pasta, but in terms of cohesiveness, resilience, adhesiveness, no significant differences were found (Rosa-Sibakov et al., 2016). Also the implementation of proteases has allowed the achievement of attracting outcomes. Renzetti & Arendt (2009) stated that brown rice breads with increased specific volume, as well as lower crumb hardness and chewiness were obtained by utilizing protease (up to 0.01%). According to the authors, the improved breadmaking performances depended on the reduction of complex modulus and initial consistency, as well as a diminished peak viscosity actuated by the proteases, but impact with proteases is highly dependent on the type or protease and the flour nature (Hamada et al., 2013).

To sum up, enzymatic technology has resulted compelling in the context of mimicking the WG behavior. As a matter of fact, the higher elasticity and resistance to deformation, as well as the continuity of the protein complex promoted by the cross-linking enzymes are key in a GF system, but more research is needed to elucidate the role of the enzymatic dosage and the function of the protein source. In addition, more attention should be paid to the polymerization degree after the enzymatic treatment; higher levels of protein aggregation may lead to a stiff system most prone to breakage and incapable to retain gas during proofing and baking. Worthy of attention in GF products manufacturing is the similarity of the active site of microbial transglutaminase to that of the tissue transglutaminase, because it could provoke immunoreactivity in celiac patients (Matthias et al., 2016). On the other side, the proteolytic activity, carried out by the proteases, releases low molecular weight proteins that would interlink with starch, forming a fine network which is responsible for the changes of the rheological behavior and pasting properties. These modifications seem to be related to greater batter deformability that would stabilize the gas cell walls, preventing their early rupture during proofing and oven spring with consequent higher expansion after baking (Renzetti & Rosell, 2016). The great variability of the raw materials and the different classes of enzymes utilized in the GF technology avoid to make general statements and make the scaling up a tough challenge. Future directions should integrate a holistic approach to optimize the enzymatic concentrations and the process conditions, with special emphasis on the synergy and antagonism among enzymes in food matrices.

3.6 Emulsifiers

Different types of emulsifiers have found application in GF products development, appearing as a feasible path for the WG replacement (Nunes et al., 2009; Gasparre et al., 2019). In GF bread making they act as gas bubbles stabilizers during proofing (Matos & Rosell, 2015), while in extrusion they behave as lubricants and by regulating starch swelling and amylose leaching during cooking, they increase firmness and reduce adhesiveness in GF pasta-like products. Nevertheless, given the diverse chemical structure of the emulsifier compounds, functionality must be checked in the specific GF system. The addition of emulsifiers might favor new interactions increasing dynamic moduli (G' and G'') (Sciarini et al., 2010). Nevertheless, emulsifiers contribution is not sufficient to resembling wheat pasta in terms of elasticity and sensory properties (Schoenlechner et al., 2010). Their interactions with starch, especially with amylose chains is of critical importance not only for the technological features, but also regarding the shelf-life of baked GF products. In the case of pasta-like goods, water distribution is affected by the amphiphilic nature of these compounds and consequently more knowledge is required to clarify their effect during the drying steps.

4. Conclusion remarks and future trends

Gluten development is essential for imparting desirable qualities to the cereal-based products like bread or pasta. The creation of non-covalent interactions and disulfide bonds, between gliadins and glutenins are pivotal in building an elastic network. The three-dimensional structure of the wheat gluten network assures the essential gas retention required for expanded and spongy loaves, while in pasta-like products it helps to prevent solid loss during cooking, guaranteeing final higher firmness and less stickiness. If wheat gluten is lacking, the dough system losses extensibility and elasticity with consequent deterioration of the food product sensory properties. This is the case of the gluten-free food products that have been at the center of numerous technological advances in the twenty years. In fact, their basic formulations, mainly flours and/or starches from different sources are not able to replicate the wheat-based food products features. Protein addition, physical treatments, enzymatic technology, hydrocolloids and emulsifiers have been successfully applied to generate a pseudo wheat gluten network. This progression has improved the gluten-free products, but the comparison with their wheat-based counterparts still highlights deep differences in terms of appearance, texture and sensory properties. One potential path for the future, therefore, might be deepening the understanding of the synergies between the adoption of different physical technologies and various processing aids. In addition to that, a greater deepening about the role of non-gluten protein polymerization, in defining the quality of GF end products is needed for a better understanding of the weight of all the existing variables in a complex GF system. The optimization gluten-free formulations could also come from the search for raw materials already containing those functional ingredients, which have proven to be fundamental in building a three-dimensional network. In this regard, minor cereals, such as wild rice, fonio, teosinte and canary seeds have been little explored. Powders form acorn and carob have shown a good potential in GF food technology but their presence in the market is still limited. By utilizing oilseeds by-products (rapeseed and sunflower), which contain sulfur-rich amino acids not only could be a valuable strategy under a technological and nutritional standpoint, but also can help the shift towards a more sustainable production in accordance with the circular economy principles.

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References

Alvarez-Jubete, L., Auty, M., Arendt, E. K., & Gallagher, E. (2009). Baking properties and microstructure of pseudocereal flours in gluten-free bread formulations. *European Food Research and Technology*, *230*(3), 437. https://doi.org/10.1007/s00217-009-1184-z

Baudouin, F., Nogueira, T. L., van der Mijnsbrugge, A., Frederix, S., Redl, A., & Morel, M.-H. (2020). Mechanochemical activation of gluten network development during dough mixing. *Journal of Food Engineering*, *283*, 110035. https://doi.org/10.1016/j.jfoodeng.2020.110035

Beccari, J. B. (1745). De frumento. *De Bononiensi Scientiarum et Artium Atque Academia Commentarii, Tomi Secundi. Bononia*.

Bell, G. D. H. (1987). The history of wheat cultivation. In F. G. H. Lupton (Ed.), *Wheat Breeding: Its scientific basis* (pp. 31–49). Springer Netherlands. https://doi.org/10.1007/978-94-009-3131-2_2

Belton, P. S. (1999). On the elasticity of wheat gluten. *Journal of Cereal Science*, *29*(2), 103–107. https://doi.org/10.1006/jcrs.1998.0227

Boulemkahel, S., Garzon, R., Benatallah, L., & Rosell, C. M. (2022). Development of gluten-free bread using low-pressure homogenized rice flour supplemented with faba bean flour. *Cereal Chemistry*, *99*(2), 368–379. https://doi.org/10.1002/cche.10498

Bourekoua, H., Benatallah, L., Zidoune, M. N., & Rosell, C. M. (2016). Developing gluten free bakery improvers by hydrothermal treatment of rice and corn flours. *Lwt-Food Science and Technology*, *73*, 342–350. https://doi.org/10.1016/j.lwt.2016.06.032

Cai, J., Chiang, J. H., Tan, M. Y. P., Saw, L. K., Xu, Y., & Ngan-Loong, M. N. (2016). Physicochemical properties of hydrothermally treated glutinous rice flour and xanthan gum mixture and its application in gluten-free noodles. *Journal of Food Engineering*, *186*, 1–9. https://doi.org/10.1016/j.jfoodeng.2016.03.033

Calle, J., Benavent-Gil, Y., & Rosell, C. M. (2020). Development of gluten free breads from *Colocasia esculenta* flour blended with hydrocolloids and enzymes. *Food Hydrocolloids*, *98*, 105243. https://doi.org/10.1016/j.foodhyd.2019.105243

Collar, C., Conte, P., Fadda, C., & Piga, A. (2015). Gluten-free dough-making of specialty breads: Significance of blended starches, flours and additives on dough behaviour. *Food Science and Technology International*, *21*(7), 523–536. https://doi.org/10.1177/1082013214552862

Cornejo, F., & Rosell, C. M. (2015). Physicochemical properties of long rice grain varieties in relation to gluten free bread quality. *Lwt-Food Science and Technology*, *62*(2), 1203–1210. https://doi.org/10.1016/j.lwt.2015.01.050

Cubadda, R. E., Carcea, M., Marconi, E., & Trivisonno, M. C. (2007). Influence of gluten proteins and drying temperature on the cooking quality of durum wheat pasta. *Cereal Chemistry*, *84*(1), 48–55. https://doi.org/10.1094/CCHEM-84-1-0048

de la Hera, E., Talegon, M., Caballero, P., & Gomez, M. (2013). Influence of maize flour particle size on gluten-free breadmaking. *Journal of the Science of Food and Agriculture*, *93*(4), 924–932. https://doi.org/10.1002/jsfa.5826

Detchewa, P., Prasajak, P., Phungamngoen, C., Sriwichai, W., Naivikul, O., & Moongngarm, A. (2022). Substitution of rice flour with rice protein improved quality of gluten-free rice spaghetti processed using single screw extrusion. *Lwt-Food Science and Technology*, *153*, 112512. https://doi.org/10.1016/j.lwt.2021.112512

Ebling, C. D., Thys, R. C. S., & Klein, M. P. (2022). Influence of amyloglucosidase, glucose oxidase, and transglutaminase on the technological quality of gluten-free bread. *Cereal Chemistry*, *99*(4), 802–810. https://doi.org/10.1002/cche.10537

Espinosa-Ramirez, J., Garzon, R., Serna-Saldivar, S. O., & Rosell, C. M. (2018). Functional and nutritional replacement of gluten in gluten-free yeast-leavened breads by using β-conglycinin concentrate extracted from soybean flour. *Food Hydrocolloids*, *84*, 353–360. https://doi.org/10.1016/j.foodhyd.2018.06.021

Fukushima, D. (2011). 8—Soy proteins. In G. O. Phillips & P. A. Williams (Eds.), *Handbook of Food Proteins* (pp. 210–232). Woodhead Publishing. https://doi.org/10.1533/9780857093639.210

Gao, Y., Janes, M. E., Chaiya, B., Brennan, M. A., Brennan, C. S., & Prinyawiwatkul, W. (2018). Gluten-free bakery and pasta products: Prevalence and quality improvement. *International Journal of Food Science and Technology*, *53*(1), 19–32. https://doi.org/10.1111/ijfs.13505

Gasparre, N., Betoret, E., & Rosell, C. M. (2019). Quality indicators and heat damage of dried and cooked gluten free spaghetti. *Plant Foods for Human Nutrition*, *74*(4), 481–488. https://doi.org/10.1007/s11130-019-00765-3

Gasparre, N., & Rosell, C. M. (2019). Role of hydrocolloids in gluten free noodles made with tiger nut flour as non-conventional powder. *Food Hydrocolloids*, *97*, 105194. https://doi.org/10.1016/j.foodhyd.2019.105194

Google Trends. (2022). *Explore search interest for gluten free by time, location and popularity on Google Trends*. Google Trends. https://trends.google.com/trends/explore?date=all&q=Gluten%20free

Grenier, D., Rondeau-Mouro, C., Dedey, K. B., Morel, M.-H., & Lucas, T. (2021). Gas cell opening in bread dough during baking. *Trends in Food Science & Technology*, *109*, 482–498. https://doi.org/10.1016/j.tifs.2021.01.032

Grosch, W., & Wieser, H. (1999). Redox reactions in wheat dough as affected by ascorbic acid. *Journal of Cereal Science*, *29*(1), 1–16. https://doi.org/10.1006/jcrs.1998.0218

Guerrero, P., Kerry, J. P., & de la Caba, K. (2014). FTIR characterization of protein–polysaccharide interactions in extruded blends. *Carbohydrate Polymers*, *111*, 598–605. https://doi.org/10.1016/j.carbpol.2014.05.005

Gujral, H. S., & Rosell, C. M. (2004a). Improvement of the breadmaking quality of rice flour by glucose oxidase. *Food Research International*, *37*(1), 75–81. https://doi.org/10.1016/j.foodres.2003.08.001

Gujral, H. S., & Rosell, C. M. (2004b). Functionality of rice flour modified with a microbial transglutaminase. *Journal of Cereal Science*, *39*(2), 225–230. https://doi.org/10.1016/j.jcs.2003.10.004

Hamada, S., Suzuki, K., Aoki, N., & Suzuki, Y. (2013). Improvements in the qualities of gluten-free bread after using a protease obtained from Aspergillus oryzae. *Journal of Cereal Science*, *57*(1), 91–97. https://doi.org/10.1016/j.jcs.2012.10.008

Hayman, D., Sipes, K., Hoseney, R. C., & Faubion, J. M. (1998). Factors controlling gas cell failure in bread dough. *Cereal Chemistry*, *75*(5), 585–589. https://doi.org/10.1094/CCHEM.1998.75.5.585

Horstmann, S. W., Foschia, M., & Arendt, E. K. (2017). Correlation analysis of protein quality characteristics with gluten-free bread properties. *Food & Function*, *8*(7), 2465–2474. https://doi.org/10.1039/C7FO00415J

Iuga, M., & Mironeasa, S. (2020). A review of the hydrothermal treatments impact on starch based systems properties. *Critical Reviews in Food Science and Nutrition*, *60*(22), 3890–3915. https://doi.org/10.1080/10408398.2019.1664978

Jacobs, H., & Delcour, J. A. (1998). Hydrothermal modifications of granular starch, with retention of the granular structure: A review. *Journal of Agricultural and Food Chemistry*, *46*(8), 2895–2905. https://doi.org/10.1021/jf980169k

Jekle, M., & Becker, T. (2015). Wheat dough microstructure: The relation between visual structure and mechanical behavior. *Critical Reviews in Food Science and Nutrition*, *55*(3), 369–382. https://doi.org/10.1080/10408398.2012.656476

Kasarda, D. (1989). Glutenin structure in relation to wheat quality. *Wheat Is Unique*, *277*, 302.

Khuzwayo, T. A., Taylor, J. R. N., & Taylor, J. (2020). Influence of dough sheeting, flour pre-gelatinization and zein inclusion on maize bread dough functionality. *Lwt-Food Science and Technology*, *121*, 108993. https://doi.org/10.1016/j.lwt.2019.108993

Kim, Y., Kee, J. I., Lee, S., & Yoo, S.-H. (2014). Quality improvement of rice noodle restructured with rice protein isolate and transglutaminase. *Food Chemistry*, *145*, 409–416. https://doi.org/10.1016/j.foodchem.2013.08.078

Lai, H.-M. (2002). Effects of rice properties and emulsifiers on the quality of rice pasta. *Journal of the Science of Food and Agriculture*, *82*(2), 203–216. https://doi.org/10.1002/jsfa.1019

Lamacchia, C., Di Luccia, A., Baiano, A., Gambacorta, G., la Gatta, B., Pati, S., & La Notte, E. (2007). Changes in pasta proteins induced by drying cycles and their relationship to cooking behaviour. *Journal of Cereal Science*, *46*(1), 58–63. https://doi.org/10.1016/j.jcs.2006.12.004

Liu, S., Yuan, T. Z., Wang, X., Reimer, M., Isaak, C., & Ai, Y. (2019). Behaviors of starches evaluated at high heating temperatures using a new model of Rapid Visco Analyzer – RVA 4800. *Food Hydrocolloids*, *94*, 217–228. https://doi.org/10.1016/j.foodhyd.2019.03.015

MacRitchie, F., Du Cros, D., & Wrigley, C. (1990). Flour polypeptides related to wheat quality. *Advances in Cereal Science and Technology*, *10*, 79–145.

Marco, C., Pérez, G., León, A. E., & Rosell, C. M. (2008). Effect of transglutaminase on protein electrophoretic pattern of rice, soybean, and rice-soybean blends. *Cereal Chemistry*, *85*(1), 59–64. https://doi.org/10.1094/CCHEM-85-1-0059

Marti, A., Barbiroli, A., Marengo, M., Fongaro, L., Iametti, S., & Pagani, M. A. (2014). Structuring and texturing gluten-free pasta: Egg albumen or whey proteins? *European Food Research and Technology*, *238*(2), 217–224. https://doi.org/10.1007/s00217-013-2097-4

Marti, A., & Pagani, M. A. (2013). What can play the role of gluten in gluten free pasta? *Trends in Food Science & Technology*, *31*(1), 63–71. https://doi.org/10.1016/j.tifs.2013.03.001

Martin, C., Morel, M.-H., Reau, A., & Cuq, B. (2019). Kinetics of gluten protein-insolubilisation during pasta processing: Decoupling between time- and temperature-dependent effects. *Journal of Cereal Science*, *88*, 103–109. https://doi.org/10.1016/j.jcs.2019.05.014

Martínez, M. M., & Gómez, M. (2017). Rheological and microstructural evolution of the most common gluten-free flours and starches during bread fermentation and baking. *Journal of Food Engineering*, *197*, 78–86. https://doi.org/10.1016/j.jfoodeng.2016.11.008

Matos, M. E., & Rosell, C. M. (2015). Understanding gluten-free dough for reaching breads with physical quality and nutritional balance. *Journal of the Science of Food and Agriculture*, *95*(4), 653–661. https://doi.org/10.1002/jsfa.6732

Matos, M. E., Sanz, T., & Rosell, C. M. (2014). Establishing the function of proteins on the rheological and quality properties of rice based gluten free muffins. *Food Hydrocolloids*, *35*, 150–158. https://doi.org/10.1016/j.foodhyd.2013.05.007

Matthias, T., Jeremias, P., Neidhöfer, S., & Lerner, A. (2016). The industrial food additive, microbial transglutaminase, mimics tissue transglutaminase and is immunogenic in celiac disease patients. *Autoimmunity Reviews*, *15*(12), 1111–1119. https://doi.org/10.1016/j.autrev.2016.09.011

McCarthy, D. F., Gallagher, E., Gormley, T. R., Schober, T. J., & Arendt, E. K. (2005). Application of response surface methodology in the development of gluten-free bread. *Cereal Chemistry*, *82*(5), 609–615. https://doi.org/10.1094/CC-82-0609

Miñarro, B., Albanell, E., Aguilar, N., Guamis, B., & Capellas, M. (2012). Effect of legume flours on baking characteristics of gluten-free bread. *Journal of Cereal Science*, *56*(2), 476–481. https://doi.org/10.1016/j.jcs.2012.04.012

Mir, S. A., Shah, M. A., Naik, H. R., & Zargar, I. A. (2016). Influence of hydrocolloids on dough handling and technological properties of gluten-free breads. *Trends in Food Science & Technology*, *51*, 49–57. https://doi.org/10.1016/j.tifs.2016.03.005

Moore, M., Heinbockel, M., Dockery, P., Ulmer, H., & Arendt, E. (2006). Network formation in gluten-free bread with application of transglutaminase. *Cereal Chemistry*, *83*(1), 28–36. https://doi.org/10.1094/CC-83-0028

Morreale, F., Garzon, R., & Rosell, C. M. (2018). Understanding the role of hydrocolloids viscosity and hydration in developing gluten-free bread. A study with hydroxypropylmethylcellulose. *Food Hydrocolloids*, *77*, 629–635. https://doi.org/10.1016/j.foodhyd.2017.11.004

Nunes, M. H. B., Moore, M. M., Ryan, L. A. M., & Arendt, E. K. (2009). Impact of emulsifiers on the quality and rheological properties of gluten-free breads and batters. *European Food Research and Technology*, *228*(4), 633–642. https://doi.org/10.1007/s00217-008-0972-1

Padalino, L., Mastromatteo, M., De Vita, P., Maria Ficco, D. B., & Del Nobile, M. A. (2013). Effects of hydrocolloids on chemical properties and cooking quality of gluten-free spaghetti. *International Journal of Food Science & Technology*, *48*(5), 972–983. https://doi.org/10.1111/ijfs.12049

Pagani, M. A., Gallant, D., Bouchet, B., & Resmini, P. (1986). Ultrastructure of cooked spaghetti. *Food Structure*, *5*(1), 14.

Piber, M., & Koehler, P. (2005). Identification of dehydro-ferulic acid-tyrosine in rye and wheat: Evidence for a covalent cross-link between arabinoxylans and proteins. *Journal of Agricultural and Food Chemistry*, *53*(13), 5276–5284. https://doi.org/10.1021/jf050395b

Pongjaruvat, W., Methacanon, P., Seetapan, N., Fuongfuchat, A., & Gamonpilas, C. (2014). Influence of pregelatinised tapioca starch and transglutaminase on dough rheology and quality of gluten-free jasmine rice breads. *Food Hydrocolloids*, *36*, 143–150. https://doi.org/10.1016/j.foodhyd.2013.09.004

Renzetti, S., & Arendt, E. K. (2009). Effect of protease treatment on the baking quality of brown rice bread: From textural and rheological properties to biochemistry and microstructure. *Journal of Cereal Science*, *50*(1), 22–28. https://doi.org/10.1016/j.jcs.2009.02.002

Renzetti, S., & Rosell, C. M. (2016). Role of enzymes in improving the functionality of proteins in non-wheat dough systems. *Journal of Cereal Science*, *67*, 35–45. https://doi.org/10.1016/j.jcs.2015.09.008

Roman, L., Belorio, M., & Gomez, M. (2019). Gluten-free breads: The gap between research and commercial reality. *Comprehensive Reviews in Food Science and Food Safety*, *18*(3), 690–702. https://doi.org/10.1111/1541-4337.12437

Rosa-Sibakov, N., Heinio, R., Cassan, D., Holopainen-Mantila, U., Micard, V., Lantto, R., & Sozer, N. (2016). Effect of bioprocessing and fractionation on the structural, textural and sensory properties of gluten-free faba bean pasta. *Lwt-Food Science and Technology*, *67*, 27–36. https://doi.org/10.1016/j.lwt.2015.11.032

Rosell, C. M., Altamirano-Fortoul, R., Don, C., & Dubat, A. (2013). Thermomechanically induced protein aggregation and starch structural changes in wheat flour dough. *Cereal Chemistry*, *90*(2), 89–100. https://doi.org/10.1094/CCHEM-05-12-0056-R

Rosell, C. M., Rojas, J. A., & Benedito de Barber, C. (2001). Influence of hydrocolloids on dough rheology and bread quality. *Food Hydrocolloids*, *15*(1), 75–81. https://doi.org/10.1016/S0268-005X(00)00054-0

Rosell, C. M., Yokoyama, W., & Shoemaker, C. (2011). Rheology of different hydrocolloids–rice starch blends. Effect of successive heating–cooling cycles. *Carbohydrate Polymers*, *84*(1), 373–382. https://doi.org/10.1016/j.carbpol.2010.11.047

Sahagún, M., Bravo-Núñez, Á., Báscones, G., & Gómez, M. (2018). Influence of protein source on the characteristics of gluten-free layer cakes. *Lwt-Food Science and Technology*, *94*, 50–56. https://doi.org/10.1016/j.lwt.2018.04.014

Salehi, F. (2019). Improvement of gluten-free bread and cake properties using natural hydrocolloids: A review. *Food Science & Nutrition*, *7*(11), 3391–3402. https://doi.org/10.1002/fsn3.1245

Schmid, M., Wieser, H., & Koehler, P. (2016). Isolation and characterization of high-molecular-weight (HMW) gliadins from wheat flour. *Cereal Chemistry*, *93*(6), 536–542. https://doi.org/10.1094/CCHEM-04-16-0078-R

Schoenlechner, R., Drausinger, J., Ottenschlaeger, V., Jurackova, K., & Berghofer, E. (2010). Functional properties of gluten-free pasta produced from amaranth, quinoa and buckwheat. *Plant Foods for Human Nutrition*, *65*(4), 339–349. https://doi.org/10.1007/s11130-010-0194-0

Sciarini, L. S., Ribotta, P. D., Leon, A. E., & Perez, G. T. (2010). Effect of hydrocolloids on gluten-free batter properties and bread quality. *International Journal of Food Science and Technology*, *45*(11), 2306–2312. https://doi.org/10.1111/j.1365-2621.2010.02407.x

Shewry, P. R., & Tatham, A. S. (1997). Disulphide bonds in wheat gluten proteins. *Journal of Cereal Science*, *25*(3), 207–227. https://doi.org/10.1006/jcrs.1996.0100

Shewry, P. R., Tatham, A. S., Forde, J., Kreis, M., & Miflin, B. J. (1986). The classification and nomenclature of wheat gluten proteins: A reassessment. *Journal of Cereal Science*, *4*(2), 97–106. https://doi.org/10.1016/S0733-5210(86)80012-1

Shi, M., Gao, Q., & Liu, Y. (2018). Corn, potato, and wrinkled pea starches with heat–moisture treatment: Structure and digestibility. *Cereal Chemistry*, *95*(5), 603–614. https://doi.org/10.1002/cche.10068

Srikaeo, K., Laothongsan, P., & Lerdluksamee, C. (2018). Effects of gums on physical properties, microstructure and starch digestibility of dried-natural fermented rice noodles. *International Journal of Biological Macromolecules*, *109*, 517–523. https://doi.org/10.1016/j.ijbiomac.2017.12.121

Tilley, K. A., Benjamin, R. E., Bagorogoza, K. E., Okot-Kotber, B. M., Prakash, O., & Kwen, H. (2001). Tyrosine cross-links: Molecular basis of gluten structure and function. *Journal of Agricultural and Food Chemistry*, *49*(5), 2627–2632. https://doi.org/10.1021/jf010113h

Toufeili, I., & Kokini, J. L. (2004). Glass transition behavior and rheological properties of surfactants and gluten-surfactant mixtures. *Cereal Chemistry*, *81*(5), 582–588. https://doi.org/10.1094/CCHEM.2004.81.5.582

Toufeili, I., Lambert, I. A., & Kokini, J. L. (2002). Effect of glass transition and cross-linking on rheological properties of gluten: Development of a preliminary state diagram. *Cereal Chemistry*, *79*(1), 138–142. https://doi.org/10.1094/CCHEM.2002.79.1.138

Veraverbeke, W. S., & Delcour, J. A. (2002). Wheat protein composition and properties of wheat glutenin in relation to breadmaking functionality. *Critical Reviews in Food Science and Nutrition*, *42*(3), 179–208. https://doi.org/10.1080/10408690290825510

Wang, K.-Q., Luo, S.-Z., Zhong, X.-Y., Cai, J., Jiang, S.-T., & Zheng, Z. (2017). Changes in chemical interactions and protein conformation during heat-induced wheat gluten gel formation. *Food Chemistry*, *214*, 393–399. https://doi.org/10.1016/j.foodchem.2016.07.037

Wieser, H. (2007). Chemistry of gluten proteins. *Food Microbiology*, *24*(2), 115–119. https://doi.org/10.1016/j.fm.2006.07.004

Wieser, H., Koehler, P., & Scherf, K. A. (2022). Chemistry of wheat gluten proteins: Qualitative composition. *Cereal Chemistry*, 1–13. https://doi.org/10.1002/cche.10572

Yalcin, S., & Basman, A. (2008). Effects of gelatinisation level, gum and transglutaminase on the quality characteristics of rice noodle. *International Journal of Food Science & Technology*, *43*(9), 1637–1644. https://doi.org/10.1111/j.1365-2621.2007.01674.x

Yano, H., Koda, T., Fujita, N., & Nishioka, A. (2020). Effect of amylose content in rice flour on batter rheology and bread baking quality. *Journal of Food Processing and Preservation*, *44*(6). https://doi.org/10.1111/jfpp.14462

Yao, M., Li, M., Dhital, S., Tian, Y., & Guo, B. (2020). Texture and digestion of noodles with varied gluten contents and cooking time: The view from protein matrix and inner structure. *Food Chemistry*, *315*, 126230. https://doi.org/10.1016/j.foodchem.2020.126230

Zoghi, A., Mirmahdi, R. S., & Mohammadi, M. (2021). The role of hydrocolloids in the development of gluten-free cereal-based products for coeliac patients: A review. *International Journal of Food Science & Technology*, *56*(7), 3138–3147. https://doi.org/10.1111/ijfs.14887