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Structure and quality of pasta enriched with functional ingredients

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Dry pasta is a traditional cereal-based food product that is becoming increasingly popular worldwide because of its convenience, palatability, and nutritional quality. The low cost and the long shelf life of pasta, as well as the fact that it is consumed by people of all ages and from all walks of life, make this a suitable product to be enriched with functional ingredients of various types and origins. In this article we review current knowledge on the fate of those functional components that have been more widely studied, how they may interact during processing and what impact they may have on quality attributes. In particular, the specific interactions between key components (starch and proteins) during lamination, extrusion and drying are reviewed. As far as we know, few review articles consider the addition of different types of functional ingredients of various physicochemical properties to pasta formulation or how such addition affects pasta quality.

Introduction

Pasta is a traditional cereal based food in the Mediterranean diet, usually recommended because of its convenience, palatability, and nutritional quality. A low glycemic index characterizes pasta and is attributed to the successive changes in structure and the interactions between the two major components: starch and proteins. In the present review we will focus on pasta quality and how different functional ingredients added to its formulation affect its attributes. First, a brief description of the pasta technological processing cycle is given; after that, the principal attributes of a good pasta quality is detailed, along with the nutritional aspects of the final product. Since the type of wheat and processing conditions determine pasta quality, an evaluation of the protein–starch matrix development during the pasta making process is also presented. This review also highlights how organoleptic properties, texture and protein matrix integrity are affected by soluble and insoluble fibers, resistant starch, legume flours, Andean crop flours, gluten free, antioxidant and marine ingredients.

Pasta technological process cycle

In this section a brief description of the most important aspects of pasta processing are shown in order to introduce where the structural changes (discussed later) that determine pasta quality takes place.

Semolina, the prime ingredient of pasta, is the type of flour obtained from the milling of the *Triticum durum* wheat grain. Nonetheless, pasta can also be produced using flour from *Triticum aestivum* wheat,[1] the type of grain most commonly found in the world and the one chosen for breadmaking.[2]

Pasta made from bread wheat flour is commonly laminated while durum wheat pasta is extruded through dies that create the desired shape, in both cases usually followed by drying to impart storage stability. The differences between both types of wheat and processing result in two easily distinguishable products in terms of appearance and texture. Durum wheat pasta is characterized by a dense and firm texture with a yellow color, while bread wheat pasta is usually softer and more elastic than those with a very light yellow color.[2–4] The high proportion of carotenoids in durum wheat pasta is responsible for the color differences between these two wheat species.[5] In addition to wheat flour or semolina, traditional pasta also includes water in its formulation. That means water, as well as mechanical and thermal energy, is necessary to modify wheat structure, particularly starch and proteins, to create the correct final configuration that ensures a good quality.[6] Therefore, dough properties will determine the effectiveness of processing. That means hydration and gluten development must be appropriate in relation to the drying needs in the next phase, even the product shape and its handling and ventilation during all the productive process.[7–9] The variables during pasta making process are defined in relation to the need not to alter or damage the cohesion and elasticity properties and characteristics of dough which define pasta quality.[10]

Mixing

At the beginning of the pasta making process, wheat flour/semolina is mixed with water in order to assure homogeneity and diffusion into the center of flour/semolina particles and

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form a dough. During mixing, hydration must be between 29% and 32%; a lower water content does not allow the correct hydration of semolina particles, while higher levels lead to difficulties in extrusion, due to the formation of a big lump that could not enter in next stages of pasta making.[10–13] Due to that insufficient water content, the dough is not fully developed until it passes into the sheeting or extrusion stage. So that, a granular texture (lumps of 2–3 cm in diameter) of dough must be obtained at the end of the mixing.[14] The hydration of semolina/flour promotes molecular mobility of its components before dough development, enabling biochemical modifications of proteins and their interactions.[10,11] As a result a novel set of properties and cross-links that defines gluten functionality start to take place at this point.[15] Another aspect to consider in pasta processing is that mixing and kneading increase the oxygen availability through the water incorporation and of a mechanical action, increasing the carotenoids oxidation[16,17] resulting in pasta bleaching.[11,16] Lipoxygenase is one of the mayor responsible of the oxidation of polyunsaturated fatty acids that promotes carotenoids degradation.[5] The different variables that affects oxidoreducing enzymes during mixing have been deeply investigated by Delcros, *et al.*[18] Some research with a more detailed explanation of protein changes and pigment degradation could be found.[10,14,19–23]

Extrusion or lamination

After mixing, the process continued to extrusion or sheeting stages. During extrusion, dough is mixed and kneaded under very high pressure through a die to form the pasta final shape. Due to the heat generated by the pressure and friction, the extrusion process have to be extremely controlled.[24] During extrusion, the proteins interact strongly and a cross-linked matrix is formed (gluten) which will be determinant in cooking performance of final product.[11,19,20,25] The lack of work or an excess of thermal energy given to the dough could result in a not developed protein matrix or damaged by superheating.[7,25,26] The extrusion process is carried out in vacuum in order to avoid further pigment oxidation from enzyme destruction or inhibition,[18,27] and reduction of oxygen available.[28] On the other hand, some types of pasta are passed several times through sheeting rollers instead extrusion. During this process the dough is kneaded and rolled into a sheet by compression between a series of rotating cylinders pairs with decreasing roll gaps.[14] The sheet is folded several times favoring the cross-linking of protein and gluten development.[13,29,30] Usually for sheeted pasta is necessary a high moisture content of the dough during mixing.[29] As in extrusion, an excess in passing through sheeting rolls could damage the protein matrix.[13] The sheeted obtained is then is cut into strands of the desired width and length. A great research could be found focus on lamination and extrusion parameters and chemical changes that take place at this steps of pasta making process.[12,20,30–34]

Drying

After extrusion/sheeting the pasta with a 30% of moistness, have to be dry to a moisture level of about 12.5%. Drying is a crucial part of the process for production of high quality pasta products. Humidity, air flow and temperature are carefully controlled as the pasta passes through several dryers. Drying of pasta was initially carried out at low temperature (LT) 40–50 °C, then with some new technology the high drying temperature (HT) 60–90 °C was used in industrial plants. In the last decades, the adoption of high temperature short time (HTST) >90 °C drying cycles has allow the improvement of pasta cooking properties.[35] Many researchers have investigated how different drying conditions affects pasta quality.[25,36–45] The conclusions indicates that at low temperature drying the quantity and quality of proteins from raw material defines product quality, but with high temperature drying, only the quantity of proteins became significant.[37] In addition, modern high temperature drying systems besides texture, improve pasta color as it increases yellowness (b^*) and redness (a^*) due to Maillard reaction.[46–48]

Considering extruded and laminated pasta, researchers found that in the first type the protein-matrix could be more distributed and trap all starch granules than with the second one.[10,49] Besides, the major challenge is the drying process; Bonomi *et al.*[50] studied, from a molecular point of view, the influence of processing on pasta structure and concluded that the drying step is decisive in the sensory quality of pasta. These authors observed that gluten network undergoes denaturalization and becomes insoluble when pasta was dried at high temperature; as a result, the protein fraction was less sensitive to changes during cooking. Also, this matrix interferes with starch swelling and as a result, a reduced amount of water is absorbed by the pasta.[43]

Quality characteristics

Technological pasta quality

The most important pasta attributes are optimal cooking time (OCT), swelling or water uptake during cooking, texture of the cooked product, resistance to overcooking, adhesiveness and taste.[51] Cooking properties, appearance and sensorial attributes determine pasta acceptability, and also give information about the microstructure.

Color. One of the most important attributes that define pasta with good quality is its characteristic yellowness, which is easily obtained when using *durum* semolina due to its high carotenoids content as we exposed. However, when bread wheat flour is part of the formulation, additional pigments are necessary to produce pasta with acceptable yellowness and brightness. A deep amber or golden color is most preferable, usually determined with the color score[52] (values from 1 to 10) calculated as eqn (1).

$$\text{Color score} = L^*(\text{luminosity}) + (b^*(\text{yellowness}) \times 2)/20 \quad (1)$$

Optimal cooking time. When pasta in cooked, two zones could be easily distinguishable: a swollen region on the surface and the unpenetrated central core, this discontinuity moves toward the center of the sample and disappears once it has reached the Optimal Cooking Time (OCT).[2,53,54]

Cooking losses. The solids that diffuse from the pasta structure to the cooking water are known as cooking losses (CL) and this parameter is commonly used to predict pasta cooking performance; a value of 8% is considered a limit for good quality.[55] Cooking losses are calculated (eqn (2)) as the grams of solid (R) remaining after evaporation of the cooking water in which X g of pasta (P) was cooked, expressed as percentage.[20]

$$\text{CL}\ (\%) = R \times P/100 \tag{2}$$

The total organic matter (TOM) was defined by D'Egidio *et al.*[56] as a chemical method for quantitative determination of total organic matter rinsed from the pasta surface and latter modified by Dexter *et al.*[57] TOM values are expressed as grams of starch per 100 g of pasta and the proposed scale was defined as: values higher than 2.1 indicates low quality pasta, values between 2.1 and 1.4 indicates a product with good quality and values less than 1.4 correspond to pasta of very good quality.[58] This parameter is closely related to pasta adhesiveness.

Water absorption and swelling index. The quantity of water absorbed by pasta cooked at OCT (Pc) is associated with starch swelling and gelatinization and determined as the percentage of weight increase in relation to uncooked pasta (Pu) (eqn (3)).

$$\text{WA}\ (\%) = [(\text{Pc} - \text{Pu})/\text{Pu}] \times 100 \tag{3}$$

The grams of water absorbed per gram of dry pasta (Pu), named swelling index is a good indication of the integrity of protein matrix that restricts water penetration. Determination of this index is performed by drying to constant weight the cooked pasta (Pcd) and employing eqn (4).[59]

$$\text{SI} = (\text{Pc} - \text{Pcd})/\text{Pcd} \tag{4}$$

A disrupted gluten network will allow granules to absorb more water and gelatinize, so that an increase of cooked weight and swelling index will be observed.[60–62] Acceptable pasta quality is related to absorption of 150–200 g of water/100 g pasta and a swelling index of approximately 1.8, without considering pasta with additional ingredients that could affect both parameters, in addition to pasta microstructure.

Texture profile. The two main parameters used to assess pasta quality are firmness and adhesiveness.[63] Profiling the cooked sample with a texturometer (TPA) is the most widely used method; fracturability could also be measured in dry pasta.[64] A typical TPA sequence involves contacting pasta strands, compressing them, going back to the original contact point, and repeating the entire cycle for a second time[51,65–68] in order to mimic the chewing action.

Pasta firmness is defined as the peak force attained during the first compression and is closely related to the strength of protein matrix. Adhesiveness is measured as the negative work between the two cycles and is related to the quantity of amylose leached to the cooking water. Cohesiveness is defined as the ratio of the area under the second peak to the area under the first peak, which means to include the compressive work and to exclude the decompressive work.[69,70] Springiness is determined as the rate at which a deformed sample goes back to its undeformed condition after the deforming force is removed, calculated as the ratio of distance of the first half of the second peak to the distance of the first half of the first peak. Chewiness was defined as the product of hardness, cohesiveness and springiness[70] and is related to the elastic strength of the protein matrix and decreases with cooking time, due to the softening of the structure and the leaching of starch to cooking water.[53,71] To a large extent, pasta texture defines pasta acceptability, particularly firmness, which is determined by gluten fraction. The higher the amount of gluten developed during processing, the higher the force needed to produce an extension of pasta. Protein matrix integrity will also determine firmness. In this sense, the amount of residue in cooking water and the adhesiveness will be low, both of which are other determining factors for pasta quality.[57,71,72] Adhesiveness, another important texture characteristic, also usually determines product acceptability. Cooking losses are intimately related to adhesiveness since a high degree of amylose leached to the cooking water means a high degree of amylopectin remaining in the pasta surface. Dexter *et al.*[57] found that the composition of TOM was related to stickiness, meaning that surface material rich in amylopectin indicates a high adhesiveness pasta. In addition, if starch from flour/semolina used in the pasta making process gelatinizes before protein matrix development (discussed later), cooking losses will increase and so will adhesiveness.[73] To sum up, drying pasta at high temperature usually results in pasta with low adhesiveness due to the denaturalization of proteins that retards starch swelling.[42,74] This means that while firmness is mostly related to gluten formation, adhesiveness will be associated with starch gelatinization, but it is important to highlight that both aspects are intimately related.

Other cooking properties. Some authors also evaluated the resistance to overcooking by increasing the OCT by 50% and 100%.[51,62,75] Appearance in also deeply analyzed by the presence of fissures, spots or roughness principally. Volume increase is related to the density of pasta structure: a product with lower density occupies a greater volume due to the increase in water absorption by starch. The increase in volume represents a compromise between the performance of cooked product with respect to uncooked product, and the excess in water absorption due to a high starch gelatinization.[68,76]

Sensorial analysis. Pasta sensorial analysis must be standardized like with any other food. Most commonly, the attributes evaluated through a hedonic scale for consumers' acceptability test are scores between 1 to 9 and increase with quality. The main sensorial attributes evaluated in pasta products are stickiness, surface swelling, 'bite firmness/elasticity' and color.[63] Firmness is evaluated as the force applied to cut the pasta with molar teeth. In addition, stickiness is defined as a measured of the force needed to applied to detach sample from tongue, teeth and/or fingers.[77] For comparison between instrumental texture measurements and sensorial analysis a trained panel is required, a minimum of 10 to 15 judges is used.[78]

In general, pasta of excellent quality is characterized by moderate OCT, low cooking losses, water absorption and swelling index, moderate volume increase with high firmness and chewiness, but low adhesiveness. These attributes result from pasta with a consolidated and non-discontinuous protein matrix that restricts starch swelling and makes water diffusion to the core of

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the product difficult. As a result, a higher retention of amylose in the structure with less amylopectin in the surface takes place, so that low cooking losses and adhesiveness were observed.

Nutritional attributes of pasta

It is generally admitted that pasta consumption leads to a moderate glucose and insulin response due to an incomplete starch absorption in the intestinal tract.[13,79–82] As a result, pasta is classified as a slowly available carbohydrates source with moderate glycemic index.[80,81,83]

There are a large number of publications that have focused on cooked pasta structure,[25,53,60,71,84,85] describing it as a protein matrix structure that embeds gelatinized starch granules. There is a contradiction between the slow digestibility of pasta and the gelatinized state of starch that is susceptible of being attacked by α-amylase.[25,86–88] On the other hand, gluten does not inhibit the enzymatic activity by itself, in the concentration that is present in pasta structure.[83] In addition, Colonna *et al.*[83] and Fardet *et al.*[26,49,89] found that starch granules were not completely surrounded by a gluten matrix and that the porosity of this (0.5–40 μm) was high enough to allow the diffusion of α-amylase. As a result, the same authors suggested another explanation for the moderate glycemic index of pasta: the tortuosity of protein matrix and the presence of high molecular weight starch polymers naturally resistant to digestion.[90]

These findings made many research works focus on the correlation between glycemic index and microstructure of pasta. At the macroscopic level (>100 μm), the reduced starch degradation is primarily attributed to the compact texture of the product, generated during processing. At the microscopic level (0.3–100 μm) the diminished digestibility of starch is associated with the tortuosity of the matrix that limits the α-amylase action, restricting the diffusion of substrates and products[91] and also the slow degradation of gluten by pepsin and pancreatic proteases.[26,49,89] Finally, at the molecular level (0.8–50 nm), the reduced swelling of starch due to the restricted water diffusion during cooking is responsible for the incomplete hydrolysis.

In conclusion, the mechanisms that affect the slowly degradation of starch from pasta products are complex and, still today, cannot be attributed only to the structural and geometrical features of protein–starch matrix or to the structural state of starch.[82]

These nutritional features, in addition to the long conservation of dried pasta, have led to an increased focus on enriched pasta, by the incorporation of functional ingredients.[92] In addition to the improved nutritional attributes that could arise from these changes in formulation, there are many changes in pasta microstructure that must be analyzed in order to avoid, as much as possible, a detrimental effect on cooking properties.

Structural characteristics of pasta

Without taking into account the type of wheat selected for pasta making, the quality will be defined by the structure of starch and proteins and the interactions between them during processing and cooking. To obtain pasta with good cooking quality and acceptable texture attributes, it is critical to develop a protein network with a good balance between elasticity and extensibility during processing.[25,93]

A compact and cross-linked structure, stabilized by hydrogen bonding and hydrophobic interactions, generated by gluten proteins is necessary to ensure excellent pasta attributes. Water addition to wheat flour or semolina during mixing makes proteins adopt an open structure, so that hydration and swelling take place and the bonds that maintain the structure weaken.[10] When extensional forces are applied polymers are stretched, producing structure deformation and less covalent interactions; consequently disulfide bonds break and re-establish, forming an aligned matrix in the direction of the extension. With increasing mixing time the thickness of sheets decrease and the interaction between them increase.[11,94]

After mixing, although flour particles are hydrated, the gluten matrix is not completely developed and it is localized and discontinuous. Protein matrix maximum development takes place during lamination or extrusion during which the necessary energy is applied to the dough, although gluten development is not complete due to insufficient water content and low mixing energy, typical of the pasta making process.[7,29] In a well developed protein matrix starch granules remain trapped and embedded in gluten, as shown in Fig. 1A.[11,94,95] Matsuo *et al.*[19] established that protein remains with irregular edges and starch granules are distributed in the direction of the force applied during the first minutes of lamination or extrusion; at the final stage of processing, granules are completely surrounded by the gluten matrix, forming the so called protein–starch matrix.[26]

At the end of the making process, pasta is dried to bring the moisture content down to 12.5%, thus preventing the proliferation of microorganisms and reducing numerous enzymatic activities. The drying process has always been, and still is today, the most crucial phase of the entire pasta-making process.[96] During this stage the moisture and volume of pasta must be reduced uniformly and homogenously in order to avoid visible fractures and defects.[25] Furthermore, during pasta drying, the film of proteins consolidates because of three phenomena: denaturalization, polymerization and aggregation of proteins.[97]

During cooking, water penetrates the protein matrix through the fissures (Fig. 1A) of this film present on pasta surface.[53,84] As a consequence, pasta surface becomes smooth and the proteins hydrate, expand in volume and produce tensions that lead to the formation of additional fractures. Water absorption by the protein matrix generates a mobile diffusion gradient from the surface to the pasta center while gelatinization takes place.[89] These changes in matrix structure favor an increased water penetration, resulting in the softening of pasta.[89] All these phenomena create a complex and porous structure, containing a filamentous network and rests of swollen granules that give pasta internal structure a honeycomb appearance, through which water and solids are exchanged during cooking[49,53,89] (Fig. 1B and C).

It is remarkable that during cooking, water diffuses and simultaneously is absorbed, establishing the competition between two mechanisms: swelling and gelatinization of starch granules, and hydration and coagulation of proteins.[84] These

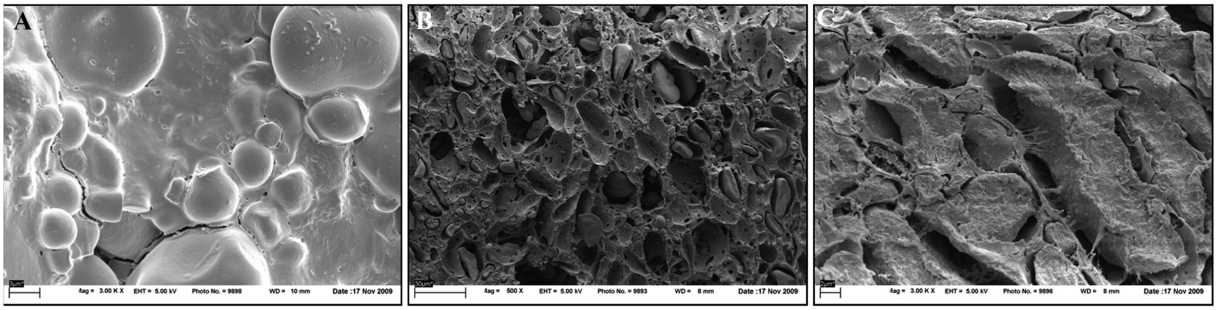

Fig. 1 Typical scanning electron microscopy (SEM) of uncooked dry pasta surface (A) and cross section of cooked pasta (B and C) made from bread wheat flour (unpublished data). Magnification 3000× (A and C) and 500× (B).

mechanisms take place at the same range of temperature and under the same humidity conditions, so both transformations are competitive and antagonist;[85] this means that both components compete for water and that starch swelling opposes to protein matrix formation. The prevalence of one of these mechanisms will define pasta cooking behavior. If protein coagulation prevails, the protein matrix consolidates and starch is trapped in that network,[25,98] water slowly penetrates and a gradual gelatinization takes place, resulting in good quality pasta.[35] On the other hand, if swelling and solubilization of starch predominate, the gluten matrix tends to breakdown with amylose release to the cooking water,[85] while amylopectin remains in the surface increasing pasta stickiness.[97]

All these mechanisms which strongly influence pasta final quality are affected in different ways by the inclusion of functional ingredients into pasta formulation, leading in some cases to a detrimental effect on technological quality.

Functional ingredients

Today consumers are more interested in food that could prevent nutrition-related diseases.[99] The biggest health concerns nowadays are obesity and overweight; blood pressure and cholesterol have also reached pandemic dimensions, driving heart health very high up in the health concern ranking.[100]

However, consumers will not compromise taste, convenience or good quality life by choosing functional food items. They demand food items that provide additional health benefits and have the same quality they are familiar with from traditional ones. In particular, bakery products have been studied extensively in the functional food development. In addition, the incorporation of functional ingredients increases the cost of the final product and this is controversial in food items such as bread because of its very short shelf life. Biscuits, cookies and cakes are very popular products because of their convenience and long shelf life, but their high sugar and fat contents, despite the improvement in quality that could be reached by functional ingredients addition, make their final nutritional quality questionable. However, pasta has been recognized for its nutritional profile, low glycemic index, long storage life and for its consumption by people from all social groups; all these qualities make it an ideal matrix through which functional ingredients can be delivered to the consumer. Recently, much research has focused on pasta enriched by diverse ingredients to develop functional pasta with additional nutritional characteristics and to study the interaction between them, protein–starch matrix and cooking quality.[1,101–104] Since cooking properties and appearance are the two most important factors in assessing pasta quality, the objective of the present review was to draw up an overview of how the principal functional ingredients studied in recent research affect pasta structure and quality.

Dietary fiber

Dietary fiber consists of the remnants of the edible plant cell, polysaccharides, lignin, and associated substances resistant to digestion by human alimentary enzymes.[105] Fiber is the most studied functional ingredient due to the many complex carbohydrates included in its definition and associated health properties.[106]

This functional ingredient can be divided into two categories, according to their water solubility; also, health benefits are quite different between them.[107,108] Soluble fiber is easily fermentable by intestinal flora, while insoluble fiber is slowly fermented. Soluble fibers, like glucan fractions from barley and oat, guar gum and inulin,[109,110] and insoluble fibers, like wheat bran and resistant starch (discussed in a separated section),[59,111] have been widely studied in recent years.

The first aspect about dietary fiber enriched pasta is that the substitution of wheat flour or durum semolina generates a gluten dilution that usually produces a decrease in cooking time as exposed by many authors.[68,111–115] Fiber addition appears to affect pasta structure, altering protein-matrix continuity. Some authors exposed that filament-like structures were observed with insoluble pasta addition, which would disturb the gluten matrix[59,68,111,115,116] (Fig. 2A).

Cooking loss is one of the parameters of cooked pasta quality most affected; the increase documented by many researchers is due to the fiber within the pasta structure which interferes with the starch–gluten network, allowing more gelatinized starch to leach from the pasta during cooking.[110,117,118]

In particular, soluble fibers have been reported to compete with starch for binding with protein, generating weak starch–protein interactions (Fig. 2B). High viscous soluble fibers like carboxymethylcellulose or guar gum presented no significant effect on technological quality when the substitution was up to 0.75% or 20%, respectively.[119] The same authors exposed that both fibers impart a surface roughness and rubbery texture in enriched pasta. Different types of β-glucans from oat and barley have been studied and reported to not have a notable effect on hardness,[120] but caused detrimental changes in cooking loss and adhesiveness.[110,121,122]

A special type of soluble fiber is inulin, which is highly soluble but does not generate viscous solutions.[123] Inulin enriched pasta has been the focus of a few papers that present contradictory results. This highly hygroscopic fiber competes with starch and protein for water, although inulin could hydrate more quickly than those components of wheat flour. If this process takes place during pasta making, inulin addition will make starch and protein fractions of pasta more discrete and less incorporated into the protein matrix, as put forward by some authors.[59,117,118] Although inulin is highly soluble in water, those authors did not evaluate the type of solid loss during cooking, while Bustos *et al.*[68] determined that almost all fiber was transferred to cooking water and that inulin incorporation in laminated pasta products was not appropriate. These results clearly indicate that more detailed studies of inulin enriched pasta would be necessary.

Considering insoluble fiber enriched pasta, whole wheat or bran wheat are the two types of fiber most widely used in pasta formulations. Both types of fiber addition appear to interfere with protein matrix development, so that, high cooking losses have also been reported.[111,116,124] These authors have observed that bran particles remain almost intact, generating a disruption in protein–starch matrix when whole-wheat flour and semolina blended with bran fiber were used in manufacturing spaghetti.

In many cases, insoluble fiber is frequently presented as a system that strongly influences the organoleptic characteristics of pasta, affecting consumer acceptability, especially considering firmness and color.[114,122,125] Regarding this, a clear understanding of color changes substantiated by evidence of the health benefits of these compounds must be given to consumers so that they can make educated food choices.[113]

Resistant starch

Dietary fiber is classically defined as non-starch polysaccharides that are not digested in the small intestine and enter the colon to be fermented, as discussed in the previous section. However, it is generally accepted that many other sources of non-digestible carbohydrates fall under this definition as well.[126] One example of this is that the digestion of resistant starch (RS) results in significant flora modulation and production of short chain fatty acids, in particular propionate and butyrate, which may have the potential to reduce risks of developing colorectal cancer.[127] This means that resistant starch (RS) deserves a particular mention in this review, considering all the research available in recent years and the nutritional benefits associated with its inclusion in pasta formulation.

Resistant starch is classified into four types:[128]

(1) Type I: starch that is physically inaccessible for digestive enzymes, *e.g.* grains and seeds.

(2) Type II: ungelatinized resistant starch granules.

(3) Type III: starch mainly represented as recrystallized (retrograded) starch, and.

(4) Type IV: chemically modified starches due to cross-bonding with chemical reagents.

Resistant starch has a low water holding-capacity; it swells and promotes viscosity increase and is useful in a variety of foods; RS types II and IV are the most commonly used in baked goods.[129] RS is characterized by high gelatinization temperature, better extrusion and film-forming qualities than traditional fiber ingredients.[130] RS type II and IV have been associated to inhibition of α-amylase for porcine pancreas which could explain the low glycemic index associated to RS enriched products.[131,132]

RS enriched pasta has been related to a slightly affected or not affected optimal cooking time,[127,133] since this type of fiber could be easily included in pasta structure as observed by SEM.[116,131] In addition, similar or lower cooking loss values were found in RSII and RSIV enriched pasta, clearly indicating that protein matrix integrity was maintained, in comparison to that of 100% semolina pasta.[116,127,134,135] Consequently, these authors found that texture analysis indicated a good pasta quality, with conserved firmness and increased chewiness, but the resultant pasta was lighter in color. Aravind *et al.*[133] showed that RS inclusion in pasta structure supposes a reduction in firmness due to a decrease in gluten, although this fact can be balanced against reduced starch swelling tendency as RS content increases. This would make pasta firmer and may explain the small change in firmness observed in RS pastas.

Therefore, RS allows for the production of high-fiber products with improved texture and appearance and less gritty mouthfeel, while it masks its lack of flavor, compared to insoluble fibers.[130]

Considering all these good results, nowadays scientists realize that starch properties are critical for cooking quality; besides, good cooking behavior is positively correlated to a high content of protein in semolina and depends on gluten promptness to reticulate.[97,136,137]

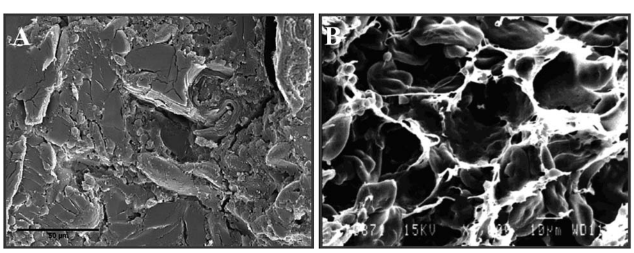

Fig. 2 SEM of cross section of uncooked spaghetti with bran (A) (Fig. 5C from ref. 111) and guar gum (B) (Fig. 1C from ref. 59) inclusion. Magnification 1000×.

Legume flours

Considering non-traditional raw materials, legumes represent an interesting source of proteins, fibers, vitamins and minerals.

However, depending on the substitution level, the pasta making process could be more or less difficult.[138]

Chickpea and soy flour are the two most studied legume flours included in pasta formulation. Particularly, soy protein content (≈40%) is higher than other legume grains (around 20–30%) or cereals (between 8–15%),[139] and has one of the most complete aminoacid profiles, compared to other protein vegetables sources.[140] Furthermore, legume flours contain no gluten, which means that semolina or flour proteins are effectively diluted with substitution, leading to a weak protein matrix and a decrease in spaghetti firmness, as some authors have discussed.[1,76,141,142] These observations clearly indicate that the decisive element in spaghetti firmness is not the protein content itself but the gluten content and possible gluten composition.

Pea, lentil, chickpea and defatted soy flours have been tested and results indicated that spaghetti made with a maximum of 30% of substitution presented an increase in firmness and color intensity, but overall quality decrease.[141,143] Legume flours included into pasta formulation have been associated with particle aggregation, which renders the feeding of the extrusion screw difficult during mixing; in addition, the introduction of non-gluten proteins affected the structure of pasta and thus its cooking quality and textural properties.[138] In general, legume flours with a maximum of 10% of semolina substitution are acceptable, despite the detrimental effects in cooking quality, particularly cooking losses and stickiness increase observed at higher addition levels.[142,144–146]

Andean crop flours

Andean crop flours inclusion in bread have been extensively studied, although their addition into pasta formulation is quite limited, with the exception of *Amaranthus* species flours that have been the focus of some research.[147–149] That could be probably because these types of crops are underused and cultivated in small plots in Bolivia, Ecuador, and Peru, at elevations of up to 4400 m in dry desert and semi-desert climates.[140]

Amaranth grain have been extensively recognized for its high nutritional properties, regarding the quality of proteins and lipids which is generally higher than those found in commercial varieties of common cereals.[140] Bejosano and Corke[150] suggest that pasta represents a complex system and that the strengthening of dough observed following addition of amaranth flours should not be expected to necessarily result in improved cooked noodle properties. As we discussed for legume flour, pasta prepared with amaranth flour also showed a clear tendency to become weaker at higher substitution levels, with increased cooking losses.[146,151]

Quinoa is another Andean crop that has been the focus of some research in recent years. Chillo *et al.*[152] reported results which were quite similar to those of *Amaranthus* spaghetti. In comparison to semolina pasta, the same authors indicated that quinoa produced a softening of dough which led spaghetti to lose their mechanical properties in the presence of water.

Both amaranth and quinoa flours have been also used in formulation of gluten-free pasta.[147,148] The most limiting factors in Andean crop flours incorporation into pasta are taste and palatability of final product, due to the presence of less hydrated teguments particles.[149]

Gluten-free pasta

In the last few decades, another group of pasta products, gluten-free (GF), is being consumed not only by the growing number of celiac people, but also by others who wish to exclude gluten-based products from their diet for health reasons.[103]

In gluten-free pasta the major challenge is gluten replacement associated to its technological role within the pasta system as its architectural key. As a result, starch will be a key component in GF pasta because the reorganization of its macromolecular structure provides good texture and overall quality.[153,154] This means that the role of gluten must be replaced by selecting appropriate ingredients, generally by using heat-treated flour as the most studied option, or by applying a modified pasta-making process to generate the necessary rearrangements of starch molecules.[155] Modifications in starch organization through the various technological steps have to lead to a three dimensional network able to mimic the viscoelastic properties of gluten, which implies a high degree of gelatinization and retrogradation, the latter being responsible for network stabilization.[156] This fact leads to the conclusion that starch for GF pasta should have a great tendency to retrograde: this property (common in high amylose starches) allows to reach good cooking quality in terms of texture and low cooking loss.[157,158]

Considering pasta production there are two main ingredients that have been the focus of recent research: gluten-free starches and, most common in recent years, gluten-free flours; in both cases the most studied sources are rice (*Oryza sativa* L.), maize (*Zea mays* L.) and Andean crops, which are distant relatives of wheat and are known to be safe for celiac people.[159,160] In both types of ingredients, starch still has a structuring role due to its tendency to re-associate and interact after gelatinization, resulting in a new organized matrix that retard further swelling and solubilization during pasta cooking.[152,154] In this sense, to reach a good technological replacement of gluten, many additives such as protein, gum, hydrocolloids and emulsifiers are frequently used; the appropriate selection of them is necessary to promote a cohesive mass in the final product[161,162] (Fig. 3).

Hydrocolloids more widely used have been: Arabic gum, xanthan-gum, locust bean gum, carboxymethylcellulose. These additives modify overall quality of pasta, providing viscosity and improving firmness and mouthfeel; they can be used alone or in combination. Due to their ability to bind water, gums can increase the rehydration rate of pasta upon cooking.[163] In addition, emulsifiers act as lubricants in the extrusion process and provide firmer consistency, a less sticky surface (Fig. 4) and decreased cooking losses. This is due to the formation of an emulsifier–amylose complex during cooking which leads to a low starch swelling and leaching phenomena.[164] Despite the

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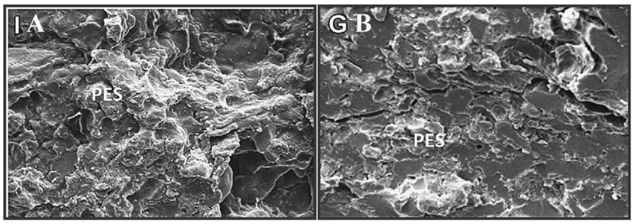

Fig. 3 SEM of cross section of cooked spaghetti made from toasted flours (soy, channa and sorghum) (A) and pasta made from same toasted flours with HPLMC, xanthan and guar gum addition (B). Magnification 2000× (Fig. 6I and G from ref. 162).

positive effects of the addition of emulsifiers and/or hydrocolloids, consumers commonly associate them with an "artificial" food product.[103] Consequently, the use of proteins as structure building ingredients represents an alternative to GF pasta because they also improve pasta nutritional properties, as observed by Cabrera-Chávez *et al.*[165] in rice pasta enriched with amaranth flour.

Considering pasta-making process, the alternative to using pre-heated starches or flours is an extrusion-cooking process where native flour is treated with steam and extruded at high temperatures (>100 °C) for promoting starch gelatinization inside the extruder.[166] Other option is the use of repeated extrusion steps (at temperatures below 46 °C).[155] Pasta obtained by extrusion-cooking exhibited superior firmness, flavor, and texture after cooking, compared to pasta products prepared from the same flour using a conventional extruder.[103,153,167] On the other hand, in pre-heated flours and starches the effect of gelatinization extent on the final product depended on the cereal variety and processing conditions used.[103,168]

In addition to the great advances in non-gluten pasta, many of the products currently in the market are of low quality, exhibiting poor structure, mouthfeel, and flavor.[169,170]

Antioxidant ingredients

Some researchers have focused on providing high antioxidant properties to cooked pasta, mainly by the addition of bran wheat.[124,171,172] In this sense, dietary fiber has been suggested to be a natural form to deliver phenolic compounds into the gut, together with other nutritional characteristics, preserving them from gastric degradation.[173,174] In addition, cereal based products made from whole wheat contain more vitamins, minerals and antioxidants and dietary fiber than those made from refined ones.[175]

Hidalgo *et al.*[21,22] reported that almost 50% of carotenoids and tocols from wheat flours was lost during pasta processing. In addition, other authors studied the total phenolic content loss in pasta during cooking and reported that almost 40% was lost in both regular and whole commercial spaghetti.[171] In addition, Fares *et al.*[172] studied that during processing, the phenolic compounds lost were the free ones, while bonded ones were affected during cooking. These authors explains that free phenolics were lost during processing probably due to the combined impact of the addition of water and oxygen, while bounded phenolics increased during cooking, which led to an increased antioxidant activity. The increase in bounded phenols was related to the release of these compounds from cell walls during cooking. Although, bran undesirable effects on textural and sensorial properties discussed above must be considered. Similar results were found in egg-pasta were carotenoids and tocols were mostly lost during kneading, reaching almost the 50% and 30% of the content, respectively.[176]

In the last years a few research works have focused on adding fruit extracts from grapes and berries into pasta formulation. Grape powder increases hardness and in turn generates a decrease in sensorial acceptance, probably because the product absorbs more water with the addition of fiber-rich ingredients, due to the interaction between water and hydroxyl groups of polysaccharides through hydrogen bonding.[177] However, the same authors concluded that fettuccini with 2.5% of grape powder addition presented an acceptable quality. On the other hand, the addition of elderberry juice with pectin and maize starch to pasta formulation increased the nutritional value of the final product, affecting, appearance, texture and cooking quality but conserving almost 70% of antioxidant activity.[178]

Vegetables were also included in pasta formulation, generating a decrease in water absorption with oregano and carrot leaf addition.[179] Padalino *et al.*[180] studied several types of vegetable flours in gluten-free pasta, and concluded that homogeneity, color, fiber, taste and smell were the parameters that most influenced the overall quality of dry spaghetti. The same authors also reported that with the addition of vegetable flour, the protein–starch matrix was disrupted, thus reducing the time water needs to reach the spaghetti centre during cooking. Broccoli powder and pulp were included in noodle formulation and generated an increase in swelling capacity and the disruption of the microstructure of the systems.[181] In general, the use

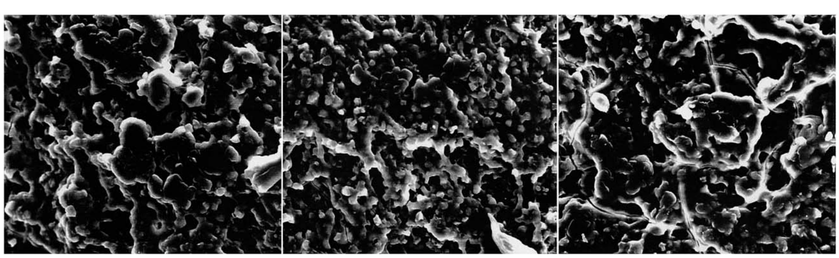

Fig. 4 SEM of rice pasta surface. At the left: pasta without any addition and dried. In the middle: steam treated pasta after extrusion. At the right: pasta with commercial emulsifier addition (Fig. 8A, B and D from ref. 164).

of plants in food supplementation can promote bitter, acrid and astringent tastes, resulting in low sensorial acceptance.[181]

The addition of high-antioxidant ingredients into pasta products is still very new; more research has to be done to determine the remaining functional compounds in cooked pasta and to evaluate more deeply the conditions of the pasta-making process that strongly affect the antioxidant capacity of final products.

Marine ingredients

The most common marine functional ingredients studied in cereal-based products are chitin, chitosan, omega-3 oils, seaweed, algae and microalgae, carotenoids, vitamins and minerals, shark cartilage and calcium in fish bone, bioactive peptides, fish protein hydrolyzates and taurine. In regard, some algae species and microencapsulated oil fish have been studied in pasta.[101]

Microalgae addition into pasta formulation creates a great change in pasta color, which some researchers have reported to be attractive for consumers.[182–184] Prabhasankar *et al.*[185] studied the incorporation of Indian brown seaweed (*S. marginatum*) and found that 2.5%- and up to 10% of flour substitution enhanced gluten network and improved cooking quality without detriment to sensorial quality. Besides, the same authors concluded that *wakame* powder up to 10% of substitution produces less undesirable changes in sensorial attributes.[186]

Chlorella vulgaris, *Spirulina maxima*, *Isochrysis galbana* and *Diacronema vlkianum* addition into pasta formulation was studied by Fradique *et al.*[182,183] where pasta quality was almost maintained. These results could be associated with the very low percentages of microalgae incorporation, up to 2 g/100 g, which produced a slight undesirable fish flavor, but improved textural characteristics, mainly firmness.

Spirulina algae biomass was also investigated by Rodriguez De Marco *et al.*[187] with decreased optimum cooking time and increased cooking loss at higher substitution level, although 20% of wheat flour substitution showed acceptable cooking properties.

Due to the taste and smell imparted by marine ingredients, these products have a low acceptance from consumers around the world; the alternative to microencapsulate active compounds, such as omega-3 fatty acids, have been explored as a way of maintaining technological and sensorial quality.[188,189]

The need to modify the sensorial attributes that the addition of marine ingredients imparts onto pasta could place these ingredients at a disadvantage in the pasta-making process, but they could be an alternative in fish based culinary preparations.

Conclusion

Functional foods generate one of the most promising developing segment of food industry and particularly pasta in not the exception. Research being conducted around the world emphasizes on developing nutritionally enhanced pasta with better cooking quality, color, and texture. Hence, there is a greater need to use some of the additives not only to improve the machinability of the dough but also to improve the quality of the end product. However, it must be highlighted here that not all of the functional ingredients can be easily incorporated in the pasta microstructure.

Future directions

Pasta serves as a staple food and could be a good food option to achieve an increased daily intake of many nutritional or functional compounds. Even when many ingredients have been included in pasta formulation to improve pasta nutritional properties, technological quality must be considered. Interactions between active compounds and protein matrix have not been deeply analyzed in all cases. In addition, only a few studies have considered synergism or interactions between individual compounds in relation to pasta products. A great number of studies have investigated gluten-free bread, focusing on the improvement of structure and technological quality through the use of additives, particularly hydrocolloids. However, non-gluten pasta has not been studied to that extent and is not comparable to bread in many aspects. All this clearly points out that more focus on the field of functional pasta and how the different ingredients affect cooking attributes are needed to reach a future diet with high quality products in terms of technological and nutritional aspects that could help reduce the risk of chronic diseases.

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