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Nutritional and Physicochemical Characteristics of Dietary Fiber Enriched Pasta

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The relationship between pasta texture and physicostructural characteristics was determined in relation to potential starch degradation and subsequent glucose release. Pastas with added soluble and insoluble dietary fiber ingredients were evaluated in relation to biochemical composition, cooking properties, and textural characteristics. Results show that both the type and amount of added fiber influence the overall quality of both raw and cooked pasta. Glucose release may be significantly reduced by the addition of soluble dietary fiber.

KEYWORDS: **Dietary fiber; nonstarch polysaccharides; starch; pasta; glucose release; digestibility; nutrition**

INTRODUCTION

Pasta is a traditional food product with origins dating back to the first century B.C. (*1*) and is favored by consumers for its ease of transportation, handling, cooking, and storage properties. In recent years pasta has become even more popular due to its nutritional properties, being regarded as a product "with low glycemic index" (*2*−*4*). Research has shown that sugars are progressively liberated from pasta during digestion, leading to low postprandial blood glucose and insulin responses in humans (*5*−*7*) and possible reduction of esophageal cancer risk (*8*).

Much research has focused on the mechanism of starch degradation in various cereal products. Both food particle size and form have been found to influence the rate of gastric emptying (*9*, *10*). Surface area accessibility to enzymes from the digestive tract appears to contribute to total degradability of food (*11*−*13*). Food structure, degree of porosity (*14*), and individual interactions among food components (starch, proteins, lipids, and dietary fibers) have also been investigated in order to understand starch behavior during in vitro and in vivo degradation (*15*−*19*). The release of starch degradation products has been found to be slower in pasta than in other cereal products, which is mainly attributed to the compact structure of pasta resulting from the extrusion process, which leads to a very close protein network entrapping starch granules and delaying α-amylase attack (*16*, *17*, *20*), and to the interactions with other components such as dietary fiber (*21*).

Potential health benefits of dietary fiber have been well documented in relation to the bowel transit time (*22*), prevention of constipation, reduction in the risk of colorectal cancer (*23*), enhanced methanogenesis (*24*), production of short-chain fatty acids (*25*−*27*), and promotion of colonic health, stimulating the growth of beneficial gut microflora (acting as prebiotics). The contribution of dietary fibers to the development of viscosity in the gut appears to be related to the control of the metabolism of glucose and lipids (*28*).

Some soluble dietary fibers, such as guar gum, have hypocholesterolemic effects (*29*), improving in this way glycemic control in diabetes. By combining the benefits of pasta (low glycemic index) with the benefits of dietary fibers (*30*), novel functional food products associated with the prevention and treatment of diseases such as coronary heart diseases and diabetes may be developed. This area of research has yet to be explored fully with a paucity of publications investigating how dietary fiber additions affect pasta quality, cooking characteristics, structure, texture, and starch digestibility.

The present study investigates possible mechanisms in lowering postprandial blood glucose after the consumption of pastas, aiming to obtain functional foods, of acceptable quality, by the inclusion of different types of dietary fiber.

MATERIALS AND METHODS

Pasta Making. Durum wheat pasta was made using commercial durum semolina (Allied Mills Ltd.), water, and different types of dietary fiber: inulin (Frutafit HD, Calleva Ltd.), guar gum (E412, Calleblend GUA, Calleva Ltd.), and pea fiber (Exafine from Cosucra Ltd.). Dietary fibers were incorporated into recipes by replacing durum wheat flour at the following proportions (w/w): pea fiber, 7.5, 10, 12.5, and 15%; inulin, 7.5, 10, 12.5, and 15%; guar gum, 3, 5, 7, and 10%. An additional sample with no dietary fiber included was also prepared as a control. Moisture contents of the pastas were adjusted on manufacture, accounting for different water absorption levels of fibers used, to produce a visually optimum dough prior to extrusion. The mixture was extruded as spaghetti (1.5 mm diameter) using a Fresco M-P15 benchtop pasta maker (Fresco Ltd.), and samples were wrapped in cling film, stored in airtight containers, and frozen at −40 °C until needed.

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Table 1. Composition and Water Uptake of Pasta Containing Different Types of Dietary Fiber[a]

fiber addition (g/100 g of DM)		DM of raw pasta (g/100 g)	DM of cooked pasta (g/100 g)	swelling index (g of water/g of dry pasta)	cooking loss (g/100 g of raw pasta)
control	0	66.06 ± 1.22^{bcd}	35.17 ± 0.53^{ab}	1.85 ± 0.04^{bc}	5.06 ± 0.11^{cde}
pea	7.5	67.30 ± 1.17^{b}	34.03 ± 0.71^{abc}	1.94 ± 0.06^{abc}	5.77 ± 0.35^{bcd}
	10	66.62 ± 0.64^{bc}	36.54 ± 0.58^{ab}	1.74 ± 0.04^{bc}	5.72 ± 0.34^{bcd}
	12.5	67.34 ± 1.40^{b}	33.47 ± 0.75^{bc}	2.00 ± 0.07^{ab}	7.41 ± 0.72^{ab}
	15	68.68 ± 1.92^{ab}	34.64 ± 0.77^{ab}	1.89 ± 0.06^{bc}	6.99 ± 0.34^{abc}
inulin	7.5	67.00 ± 0.63^{bc}	34.20 ± 0.64^{abc}	1.93 ± 0.05^{ac}	7.37 ± 0.59^{ab}
	10	67.01 ± 1.39^{bc}	33.22 ± 0.72^{bc}	2.02 ± 0.07^{ab}	6.72 ± 0.34^{abc}
	12.5	70.19 ± 0.93^{ab}	35.97 ± 0.40^{ab}	1.78 ± 0.03^{bc}	8.06 ± 0.39^{a}
	15	73.93 ± 0.88^{a}	37.76 ± 0.54^{a}	1.65 ± 0.03^{c}	7.03 ± 0.68^{abc}
guar	3	58.89 ± 1.44^{e}	35.89 ± 0.99^{ab}	1.82 ± 0.14^{bc}	3.21 ± 0.18^{f}
	5	60.94 ± 1.24^{cde}	32.91 ± 0.98^{bc}	2.05 ± 0.09^{ab}	3.87 ± 0.31^{ef}
	7	59.79 ± 1.55^{e}	32.91 ± 0.79^{bc}	2.05 ± 0.07^{ab}	4.81 ± 0.30^{def}
	10	60.28 ± 1.35^{de}	30.56 ± 0.83^{c}	2.28 ± 0.09^{a}	4.82 ± 0.25^{de}

[a] Means ± SEM. Within columns means with the same subscript are not significantly different ($P < 0.05$).

Cooking Procedure. Optimum cooking time (the time necessary to obtain complete gelatinization of starch) was determined as 7 min following standard guidelines (AFNOR NF ISO 7304, 1989) (*31*). Pasta (50 g) was cooked for 7 min in 500 mL of boiling distilled water.

After cooking and draining, samples were analyzed for swelling index, dry matter, water absorption, starch content, textural properties, and microstructure. Aliquots of cooking water were used for determination of cooking losses.

Swelling index of cooked pasta (SI; grams of water per gram of dry pasta) was evaluated by drying pasta samples to constant weight (*17*) at 105 °C, expressed as [weight of cooked product (W_1) − weight after drying (W_2)]/weight after drying (W_2) (*32*).

Dry matter was determined according to AACC Standard Method 926.07B (*33*).

Water absorption of drained pasta was determined as [[weight of cooked pasta (W_3) − weight of raw pasta (W_4)]/weight of raw pasta (W_4)] × 100.

Starch content (total starch) was determined in both raw and cooked pasta using a Megazyme starch determination kit (Megazyme International Ireland Ltd.) according to AOAC Method 996.11 (*34*) and AACC Method 76.13 (*33*).

Cooking loss in the cooking water collected from each sample was determined by evaporation to constant weight in an air oven at 105 °C. The residue was weighed and reported as percentage of the original pasta sample (*35*).

Textural characteristics of cooked pasta were determined using a Texture Analyzer TA.XT2 (Stable Micro Systems), calibrated for a load cell of 25 kg (15 replicates per sample). *Elasticity* was determined by a tension test, using the A/SPR spaghetti/noodle rig (settings: pretest speed, 3 mm/s; test speed, 3 mm/s; post-test speed, 5 mm/s; distance, 120 mm; trigger type, auto 5 g; rate for data acquisition, 200 pps). *Adhesiveness* and stickiness were determined by the adhesion test using a P35-35 mm diameter cylinder probe (settings: pretest speed, 1 mm/s; test speed, 0.5 mm/s; post-test speed, 10 mm/s; distance, 100 mm; time, 2 s; trigger type, auto 20 g; rate for data acquisition, 500 pps). *Firmness* was measured as the maximum shear strength (F_{max}) necessary for rupture of a spaghetti strand, using a Kramer cell (*17*).

Scanning Electron Microscopy (SEM). Microscopy techniques (*16*, *20*, *36*) have been used to gain information about size, shape, and arrangement of the particles, which can be further correlated with other pasta characteristics such as texture, cooking behavior, and digestibility. In the present study, the microstructure of transversely fractured raw and cooked pasta was investigated by SEM (SEM JEOL JSM6100, Oxford, U.K.) of gold-coated (using an Emitech K550 sputter coater) freeze-dried samples.

Differential scanning calorimetry (DSC) was used to measure thermal parameters (onset of gelatinization, T_o; gelatinization peak temperature, T_p; gelatinization end point, T_e; and total product enthalpy, ΔH) of raw and cooked pasta to evaluate the changes in starch at the molecular level during cooking and to assess the influence that dietary fiber might have on the properties of the starch fraction. Indium was used to calibrate the instrument (DSC 12E, Mettler Toledo). Samples were freeze-dried and milled (0.5 mm screen size). The milled sample was mixed with distilled water (1:4), to a total weight of 15 ± 0.3 mg, sealed hermetically in aluminum pans, and left to equilibrate for 1 h prior to the tests (*37*). An empty aluminum pan was used as a blank. The temperature range of the scan was 4−110 °C with a 10 °C/min heating rate.

In Vitro Digestibility of Starch. Samples of cooked pasta were cut in pieces of ∼1 mm^3, and 30 g of each sample was mixed with 100 mL of enzyme solution [51 g of α-amylase porcine (Sigma Chemical) was dissolved in 1 L of phosphate-buffered saline, pH 6.9, 0.12 M NaCl, 2.7 mM KCl, and 0.01 M phosphate-buffered salts], according to the method of Brennan et al. (*19*). The mixtures prepared were incubated at 37 °C in a shaking water bath, and samples of pasta suspensions were taken after 30, 60, and 90 min. Sample aliquots (25 mL) were cooled immediately in ice and centrifuged at 15000 rpm for 10 min. The supernatants were withdrawn and stored at −60 °C prior to glucose analysis.

Glucose analysis was determined using the Megazyme glucose assay kit (Megazyme International Ireland Ltd.) using the glucose oxidase−peroxidase (GOPOD) reagent (*38*) following recommended dilution rates. The results were expressed as milligrams of glucose per 100 mL of supernatant and milligrams of glucose per gram of starch available in the sample.

Statistical Analysis. The results from all of the tests were calculated as means ± SEM obtained from triplicate samplings of duplicate production runs and duplicate analysis determinations. Analysis of variance, followed by Tukey's test, was performed using Minitab 12.1 software (Minitab Inc.). Data obtained as percentages were arcsine transformed prior to statistical analysis.

RESULTS AND DISCUSSION

Pasta quality is influenced by a range of characteristics: physical, chemical, textural, and nutritional. For consumers, cooking quality is the most important quality attribute (*39*), including optimal cooking time, swelling or water uptake during cooking, texture of the cooked product, extent of disintegration of the cooked product, stickiness, aroma, and taste. These cooking factors of pasta are related to the gelatinization rates and chemical composition of the pasta used.

Results obtained from pasta composition and water uptake are presented in Table 1. Mean values for swelling index show no significant difference from the control other than that of guar at 10%. Values ranged from 1.67% (for pasta containing inulin at 15%) to 2.28% (for pasta containing guar at 10%), with the control sample showing an index of 1.85 (Table 1). The higher

Table 2. Texture Attributes of Cooked Pasta with Added Fiber[a]

fiber addition (g/100 g of DM)		firmness		stickiness	adhesiveness	elasticity
		peak force (N)	area (N•s)	peak force (N)	area (N•s)	peak force (N)
control	0	1.01 ± 0.04^{a}	9.46 ± 0.39^{a}	3.61 ± 0.11^{cde}	0.21 ± 0.01^{gh}	0.24 ± 0.01^{a}
pea	7.5	0.78 ± 0.03^{bcd}	6.99 ± 0.31^{cd}	3.56 ± 0.12^{cde}	0.23 ± 0.01^{fgh}	0.22 ± 0.01^{abc}
	10	0.86 ± 0.03^{abc}	7.66 ± 0.32^{bc}	3.11 ± 0.31^{ef}	0.18 ± 0.02^{hi}	0.24 ± 0.01^{ab}
	12.5	0.95 ± 0.04^{a}	8.13 ± 0.35^{abc}	3.41 ± 0.09^{def}	0.18 ± 0.01^{hi}	0.21 ± 0.01^{abc}
	15	0.77 ± 0.02^{cd}	6.93 ± 0.21^{cd}	2.76 ± 0.06^{f}	0.14 ± 0.01^{i}	0.19 ± 0.01^{cdef}
inulin	7.5	1.00 ± 0.03^{a}	9.37 ± 0.37^{a}	3.37 ± 0.09^{ef}	0.22 ± 0.01^{gh}	0.14 ± 0.01^{g}
	10	1.01 ± 0.03^{a}	9.48 ± 0.38^{a}	3.54 ± 0.10^{cde}	0.25 ± 0.01^{efg}	0.16 ± 0.01^{g}
	12.5	0.96 ± 0.03^{a}	8.92 ± 0.30^{ab}	4.93 ± 0.20^{a}	0.37 ± 0.01^{ab}	0.16 ± 0.01^{efg}
	15	0.94 ± 0.05^{a}	8.29 ± 0.37^{abc}	4.70 ± 0.19^{ab}	0.33 ± 0.01^{bcd}	0.18 ± 0.01^{def}
guar	3	1.00 ± 0.04^{a}	8.93 ± 0.29^{ab}	4.70 ± 0.15^{ab}	0.40 ± 0.01^{a}	0.20 ± 0.01^{cde}
	5	1.01 ± 0.04^{a}	8.60 ± 0.31^{ab}	4.07 ± 0.12^{bcd}	0.34 ± 0.01^{abc}	0.20 ± 0.01^{bcd}
	7	0.94 ± 0.03^{ab}	8.70 ± 0.27^{ab}	4.19 ± 0.11^{bc}	0.30 ± 0.01^{cde}	0.16 ± 0.01^{fg}
	10	0.67 ± 0.03^{d}	5.92 ± 0.31^{d}	3.76 ± 0.11^{cde}	0.28 ± 0.01^{def}	0.14 ± 0.01^{g}

[a] Means ± SEM. Within columns means with the same subscript are not significantly different ($P < 0.05$).

swelling indices obtained for the pasta containing guar gum may be explained by the higher capacity of guar to absorb and retain water within a very well developed starch−protein−polysaccharide network, in comparison to the pea and inulin fibers.

Cooking loss is a commonly used predictor of overall spaghetti cooking performance by both consumers and industry. Table 1 illustrates that increased cooking losses were obtained for the samples containing pea fiber and inulin (higher than the control, $P < 0.05$). This increase in cooking loss could be due to a disruption of the protein−starch matrix and the uneven distribution of water within the pasta matrix due to the competitive hydration tendency of the fiber, thus preventing starch swelling due to limited water availability.

Pastas containing guar gum showed reduced (guar at 3) or similar cooking loss values (guar at 5, 7, and 10%) compared with the control. This may be due to the soluble nature of the guar gum polysaccharide and the interaction that the subsequent hydrated polysaccharide network may have in encapsulating the starch−protein matrix. Such encapsulation and integration of the polysaccharide network into the pasta may strengthen the structural integrity of the pasta. This explanation is in agreement with changes in the microstructure of cereal products previously reported by Brennan et al. (*19*), who studied the interaction of guar gum in bread products.

Previous research has demonstrated a clear link between the protein content and composition of durum wheat and the cooking quality of pasta (*16*, *40*, *41*). In a review, Feillet (*42*) explained that in pasta, semolina proteins are linked together by disulfide, hydrogen, and hydrophobic bonds to form a matrix, which gives cooked pasta its viscoelastic properties. The continuity and strength of the protein matrix is dependent on the nature of inter- and intramolecular bonds. During the cooking process this matrix gradually disintegrates, releasing exudates during starch granule gelatinization, which in turn contributes to an increase in cohesiveness and stickiness on the cooked pasta surface.

Table 1 illustrates that pastas containing pea and inulin fiber (mainly insoluble fiber) have higher solids loss during cooking, possibly due to the disruption of the protein network. In the case of the pasta containing guar gum, there are different trends: small amounts of guar gum (3%) reduced solids released in the cooking water [being significantly smaller ($P < 0.05$) than for the control]. This supports the hypothesis that the gum forms a network around the starch granules, encapsulating them during cooking, and restricting excessive swelling and diffusion of the amylose content. In pasta products with 7 and 10% guar gum (Table 1), the loss of solids showed reduced rates compared to the control (although this was not significant).

The textural characteristics of pasta play an essential role in determining the final acceptance by consumers, who have shown a preference for pasta that retains texture characteristics not only with normal cooking time but also with overcooking. Results obtained in this study show that the textural characteristics of the pasta may be affected by the type and rate of fiber inclusion into pasta. Pasta firmness, elasticity, adhesiveness, and stickiness results are presented in Table 2.

Statistical analysis showed that the values for each textural attribute measured (firmness, elasticity, stickiness, and adhesiveness) were significantly different (ANOVA, $P < 0.001$) between each type of pasta studied. Tukey's test performed after ANOVA revealed the specific origins of differences (Table 2).

Firmness values of pasta containing inulin (7.5, 10, 12.5, and 15%), pea (10 and 12.5%), and guar (3, 5, and 7%) were not significantly different from the control. However, significantly reduced firmness values were obtained for pastas with pea (7.5 and 15%) and guar (10%). The general trend observed is for a progressive reduction in pasta firmness with increasing fiber concentration. The reduction in pasta firmness may be associated with the role of fiber supplements in disrupting the protein−starch matrix within the pasta microstructure.

The elasticity of pasta showed a high variation; values obtained for pastas containing pea fiber (7.5, 10, and 12.5%) were similar to the control. Pasta samples containing both inulin and guar additions showed significant reductions compared to the control. Pasta containing inulin showed an elasticity that increased with the level of inulin incorporated in the product, whereas a reverse trend was observed for pastas containing guar. This overall reduction of pasta elasticity with fiber additions relates to the disruptive behavior of fiber on the protein−starch binding during pasta matrix formation. Both stickiness and adhesiveness results (Table 2) showed similar trends: although no significant difference was recorded for adhesiveness of pasta containing pea fiber, there was a trend for a decrease of adhesiveness with increasing pea fiber concentration, which was reflected in a similar decline in pasta stickiness. Pasta with inulin fiber additions showed a general increase in adhesiveness and stickiness related to increasing fiber concentration (significant effects noted at 12.5 and 15%). Pasta with increasing levels of guar fiber showed a general reduction in adhesiveness and stickiness (although adhesiveness was still significantly higher than that of the control).

Addition of fiber appears to interfere with the structure of pasta, possibly disrupting the continuity of the protein−starch matrix, thus lowering pasta firmness compared to the control. These results parallel the results obtained by Edwards et al. (*43*), who reported that fortification of pasta with pea fiber altered its structure, resulting in moderate reduction in pasta firmness and in an increase in cooking losses. This was due to the disruptive effect pea fiber inclusion had on the protein matrix, which allowed starch granules to rupture during cooking, hence releasing high levels of amylose into the cooking water. Results from the present study support this theory, in particular, the effect of pea fiber (mainly insoluble fiber) on cooking losses and the swelling index of pasta.

Inulin additions, however, seem to influence the structure of pasta differently. Firmness values are similar to the control, suggesting that the structure remains compact, but the elasticity values are lower than the control ($P < 0.05$). This may be due to interference between inulin and the protein strands, resulting in weaker starch−protein binding. The higher values obtained for adhesiveness and stickiness (Table 2) compared to the control may be explained by the physicochemical nature of inulin fiber. Inulin is hygroscopic and competes with the starch and protein for water upon hydration. This may explain the cooking losses observed (Table 1), in that inulin hydrates more quickly than the starch and protein components of flour, in turn leading to starch and protein fractions of the pasta being more discrete and less incorporated in a matrix. On cooking, the starch is not encapsulated within a protein matrix and may form a “starchy” layer at the surface of the product, resulting in higher levels of stickiness and adhesiveness.

The interaction between guar gum and the protein−starch matrix in pasta follows a complex pattern. Low levels of guar appear to stabilize and possibly increase the firmness of pasta. However, higher levels of the guar result in a significant decrease in pasta firmness (Table 2). This observation may be related to the significantly higher moisture content ($P < 0.05$) and swelling index ($P < 0.05$) observed with increasing guar concentrations (Table 1). The higher moisture content may have an impact on mechanical properties of the system—water acting as a plasticizer of composite materials and hence increasing the flow dynamics of a system. Adhesiveness and stickiness were significantly higher than the control ($P < 0.05$); however, stickiness and adhesiveness were observed to be inversely related to fiber concentration. This may be due to the nature of the guar polysaccharide and the mode of incorporation into the pasta system. One possible explanation of the observed results is that at low levels, the guar gum is incorporated into the starch and protein matrix, becoming integral to the pasta structure and encapsulating starch granules, as observed by Brennan et al. (*19*). However, at high concentrations, guar gum (being highly hygroscopic) absorbs water to form a semisolid network. The resultant cross-linked structure may be discrete from the protein and starch matrix and indeed may inhibit structural integrity of the network, resulting in a product with a reduced elastic nature.

SEM techniques were used to investigate the structural integrity of both raw and cooked pasta. The resulting pictures appear to be supportive of the aforementioned theories. Figures 1 and 2 show micrographs obtained for raw and cooked pasta.

Micrographs of the control raw pasta samples show the protein−starch matrix to be well formed, with strong and continuous protein strands entrapping large starch granules (Figure 1a). The starch granules within this pasta appear to be slightly swollen and irregular in size and shape, perhaps indicating a level of gelatinization during the extrusion process.

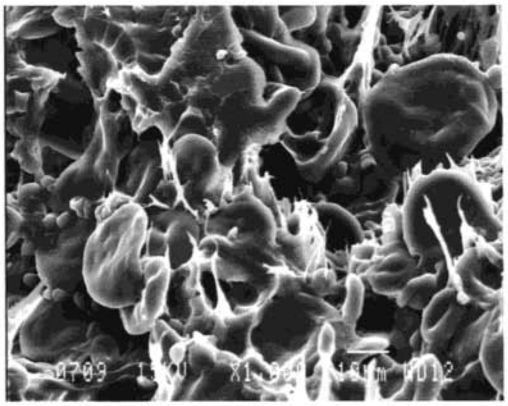
The addition of pea fiber into the product appears to disrupt the continuity of the protein matrix. The protein−fiber matrix within pasta containing pea fiber at 7.5% (Figure 1b) and 15% (Figure 1c) appears to be less developed than the control, resulting in an open appearance with discrete starch granules “uncovered” and exposed to enzymatic attack. The degree of disruption appears to increase with the amount of pea fiber added to the product. A similar effect was observed in samples containing inulin (Figure 1d, inulin at 7.5%; Figure 1e, inulin at 15%). However, in the case of the inulin fiber additions the protein−fiber−starch matrix is more continuous than for the samples containing pea fiber. The protein−starch network seems to be disrupted, but the overall pasta matrix is more compact as the fiber content increases, possibly due to greater protein−soluble fiber interactions. Micrographs of pasta with inclusion of guar at 3% (Figure 1f) show a pasta matrix similar to that of the control, with protein−starch−fiber integrating into a compact network. Starch granules within this matrix show no signs of deformation or swelling, indicating that they have not been prone to gelatinization during extrusion. SEM images of pasta with guar inclusion of 10% (Figure 1g) show starch granules enveloped in a highly developed network (probably of protein and fiber), illustrating that at higher inclusion rates of soluble fiber the binding relationship between protein and starch and fiber affects the overall structural complexity of the pasta system.

Images of cooked pasta (Figure 2) show differences related to the type and quantity of fiber included. Gelatinized starch granules within control pasta (Figure 2a) appear to be integrated in a developed protein matrix to form a compact pasta structure. However, pea fiber inclusion at 7.5% (Figure 2b) disrupts this network with starch granules within the pasta matris, losing regular structure and showing signs of gelatinization. Increasing pea fiber inclusion increases the disruption to the pasta matrix and the starch−protein−fiber network, giving rise to a highly porous structure (pea fiber at 15%, Figure 2c). This disruption to the pasta structure may explain the decreased firmness and elasticity observed in Table 2 and hence the overall textural quality of the pasta.

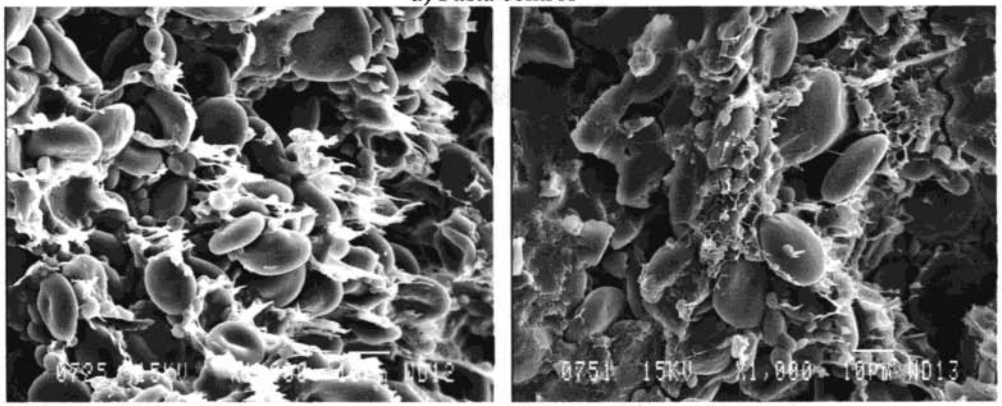
Additions of inulin at 7.5 and 15% (parts d and e, respectively, of Figure 2) appear not to affect pasta structure compared with that of the control. The protein−fiber−starch network is highly developed with discrete starch granules (showing signs of gelatinization) visible. The similarity in structure between inulin and control samples may explain the similarity in pasta firmness as observed in Table 2; however, the fiber component within the highly developed protein−fiber−starch network may decrease the starch−protein binding and hence explain the decrease in pasta elasticity.

Guar additions of 3 and 10% (parts f and g, respectively, of Figure 2) show very different pasta structures. In particular, the appearance of the starch granules is different from that observed in the control with the granules appearing to be less swollen and more regular in shape than the control samples. Micrographs of pasta with a 10% inclusion of guar (Figure 2g) show a highly compacted pasta structure where starch granules appear to be entrapped within a protein−fiber network. This may explain not only the appearance (different from the other types of pasta) but also the reduced cooking losses (Table 1) and significantly altered textural characteristics (Table 2). These results parallel the data obtained by Fardet et al. (*17*) in a study that included pasta containing soluble dietary fiber.

The effects of fiber additions in pasta on starch gelatinization properties, starch degradation rates, and hence potential sugar release were investigated using both DSC and in vitro digest-

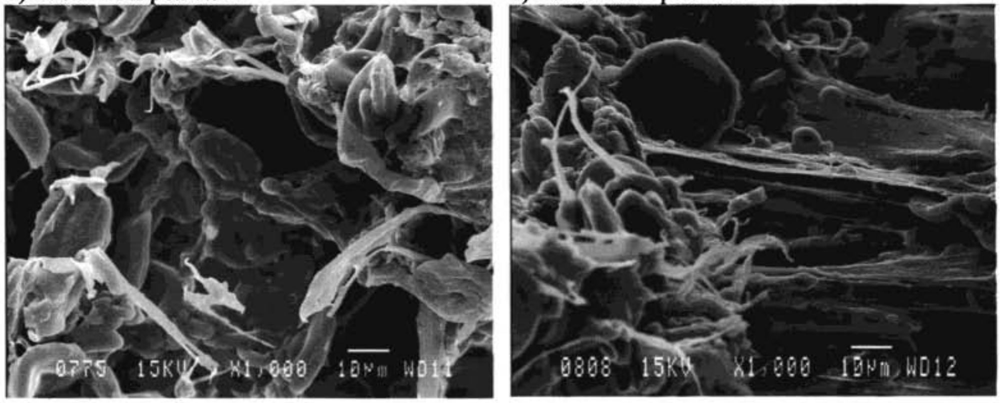


a) Pasta control



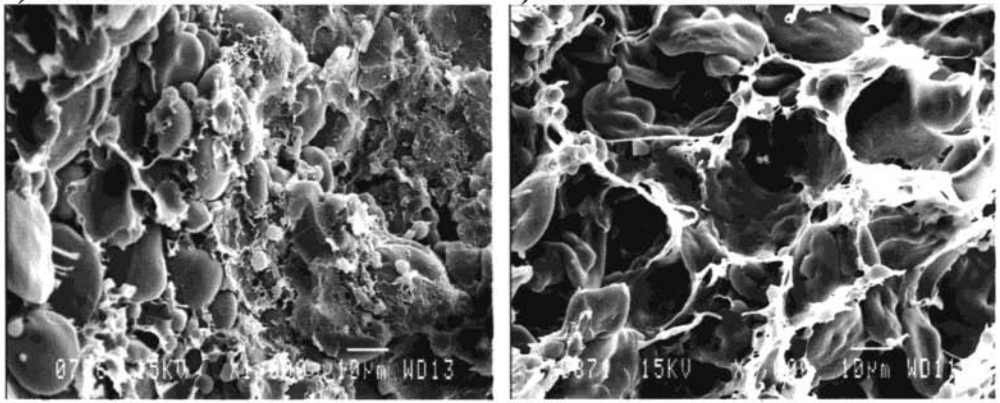
b) Pasta with pea 7.5%

c) Pasta with pea fibre 15%



d) Pasta with inulin 7.5%

e) Pasta with inulin 15%

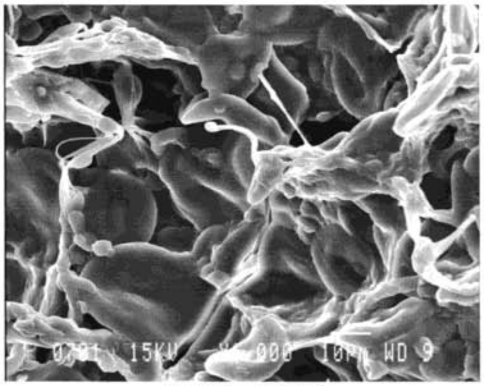


f) Pasta with guar gum 3%

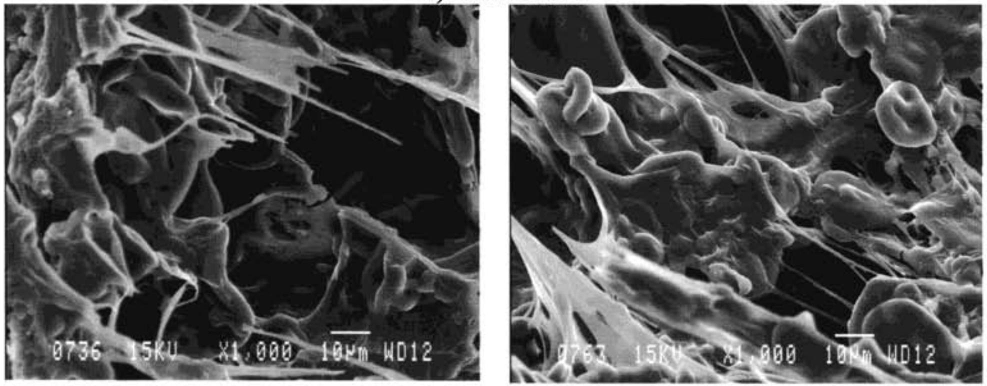
g) Pasta with guar gum 10%

Figure 1. SEM micrographs of raw pastas: (a) pasta control; (b) pasta with pea 7.5%; (c) pasta with pea fiber 15%; (d) pasta with inulin 7.5%; (e) pasta with inulin 15%; (f) pasta with guar gum 3%; (g) pasta with guar gum 10%.

ibility methodology. Results from DSC analysis of raw pasta products (Table 3) show that additions of fiber affect starch gelatinization temperatures (peak temperature values, T_p, for the pasta samples) and also the general enthalpy of the pasta

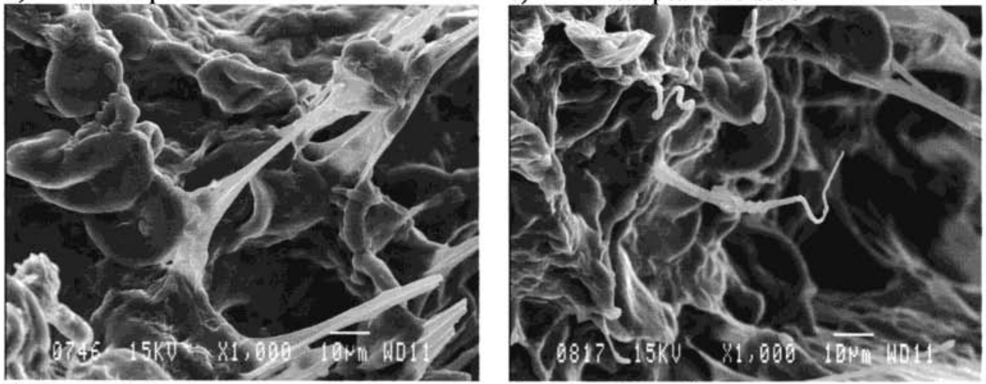


a) Pasta control



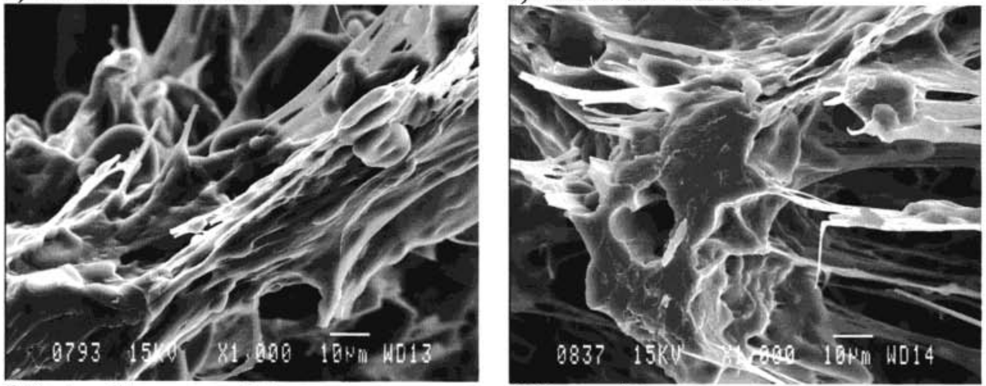
b) Pasta with pea fibre 7.5%

c) Pasta with pea fibre 15%



d) Pasta with inulin 7.5%

e) Pasta with inulin 15%



f) Pasta with guar gum 3%

g) Pasta with guar gum 10%

Figure 2. SEM micrographs of cooked pastas: (a) pasta control; (b) pasta with pea 7.5%; (c) pasta with pea fiber 15%; (d) pasta with inulin 7.5%; (e) pasta with inulin 15%; (f) pasta with guar gum 3%; (g) pasta with guar gum 10%.

mixture. The starch gelatinization temperature in the pasta containing inulin and guar showed a nonsignificant increase, whereas pasta with pea fiber additions showed gelatinization temperatures similar to that of the control sample. As such, the results are consistent with previous research (*44*, *45*) which showed that the inclusion of soluble nonstarch polysaccharides leads to an increase in gelatinization temperature. This is partly due to the soluble fibers competing with starch for water absorption and hence limiting starch swelling and gelatinization events, resulting in a higher than expected T_{endset} value.

Table 3. Thermal Gelling Properties (DSC Measurements) for Raw Pasta^{a}

fiber addition (g/100 g of DM)		T_{onset} (°C)	T_{endset} (°C)	enthalpy (ΔH, J/g)	gelatinization temp (°C)
control	0	55.10 ± 0.25	66.43 ± 0.29	0.99 ± 0.06^{a}	60.73 ± 0.22^{b}
pea	7.5	54.30 ± 0.4	67.05 ± 0.25	0.82 ± 0.01^{abc}	61.10 ± 0.1^{b}
	10	53.65 ± 0.45	67.35 ± 0.35	0.75 ± 0.03^{abcd}	60.95 ± 0.05^{b}
	12.5	53.05 ± 0.65	67.25 ± 0.15	0.68 ± 0.01^{bcd}	60.85 ± 0.05^{b}
	15	53.30 ± 0.1	66.85 ± 0.15	0.62 ± 0.01^{cde}	60.60 ± 0.2^{b}
inulin	7.5	55.70 ± 1.3	67.10 ± 0.3	0.81 ± 0.01^{abcd}	60.85 ± 0.55^{b}
	10	55.90 ± 1.8	69.70 ± 1.5	0.55 ± 0.02^{de}	61.85 ± 0.65^{b}
	12.5	55.80 ± 0.4	68.65 ± 1.45	0.36 ± 0.01^{e}	64.05 ± 0.85^{b}
	15	54.70 ± 0.8	68.00 ± 0.5	0.58 ± 0.11^{cde}	62.55 ± 0.05^{ab}
guar	3	53.90 ± 0.32	67.07 ± 0.48	0.86 ± 0.05^{ab}	61.27 ± 0.03^{b}
	5	53.70 ± 0.6	67.90 ± 0.5	0.83 ± 0.05^{abc}	61.00 ± 0.2^{b}
	7	54.57 ± 1.18	68.70 ± 1.5	0.69 ± 0.02^{bcd}	61.60 ± 0.4^{b}
	10	52.55 ± 0.05	67.00 ± 1.1	0.74 ± 0.01^{bcd}	61.65 ± 0.15^{b}

[a] Means ± SEM. Within columns means with the same subscript are not significantly different ($P < 0.05$).

Previous research conducted on model systems (*45*) found that enthalpy of starch/guar and xanthan gum mixtures increased in relation to the increasing concentrations of gum used.

Results obtained in this study suggest that the enthalpy of a flour/fiber complex decreases with increasing fiber concentration. With regard to pea fiber inclusion, the decrease in enthalpy appears to be related directly to the concentration of fiber within the system (Table 3). In both the inulin- and guar-added pasta products there is a decrease in enthalpy until a certain level of fiber inclusion is reached (12.5% in inulin, 7% in guar), after which there is an increase in enthalpy of the system.

The enthalpy of a system is an indicator of the amount of starch gelatinization within a flour or starch base and should be related to the gelatinization temperature of the starch within the system. One possible explanation for the pattern of enthalpy values of the inulin and guar systems is that at low levels of soluble fiber inclusion the fiber encapsulates the starch granules within the pasta complex and hence reduces the starch gelatinization events, whereas in higher fiber concentrations pockets of cross-linked gums form, resulting in less encapsulating of individual starch granules. This was partly observed in the SEM images of cooked pasta with added guar concentrations (Figure 2). However, more work needs to be conducted on this topic to characterize the actual gelatinization events during the cooking of pasta products with added fiber.

DSC analyses of cooked pasta products were conducted. No peak was observed between 4 and 110 °C (results not shown), indicating that complete starch gelatinization may have occurred during pasta cooking.

The effect of starch gelatinization properties on starch digestion and glucose release were investigated using in vitro digestibility studies [as in Brennan et al. (*19*)]. Values for glucose release during in vitro digestibility studies varied according to the type and quantity of fiber used in the pasta products. Pea fiber appears to increase the overall glucose release of pasta (on a milligrams per gram of DM basis), whereas both inulin and guar fiber reduce the overall glucose release from the sample (Figure 3).

Part of this decrease in glucose may be due to the reduction of starch content within the pasta, accounting for fiber inclusion. To relate the release of glucose to actual starch content within the pasta complex, the starch content of the cooked pasta was determined and the glucose release expressed as amount per gram of starch (Figure 4). Figure 4 indicates that glucose release is significantly increased ($P < 0.001$) in pasta containing pea and inulin fiber (at both 60 and 90 min during the in vitro digestibility). However, glucose release of pasta containing guar shows a significant decrease ($P < 0.001$) at 90 min.

Increased glucose release observed in pasta samples with added pea fiber may be due to the way that pea fiber disrupts the integrity of the pasta matrix. The SEM images of both raw and cooked pasta with pea fiber show signs that the starch granules within the products are not connected to the protein–fiber matrix and as such may be more susceptible to starch degradation. The similarities in gelatinization temperatures of pea and the control sample indicate that the pea fiber has no protective effect on starch granules. This is consistent with the observations of Edwards et al. (*43*, *46*), who found that the inclusion of pea fiber resulted in a breakdown of the starch–protein continuum and increased the accessibility of starch-degrading enzymes to the starch, resulting in an increased level of amylose leakage during gelatinization.

The role of inulin in controlling glucose release may be related to the way inulin becomes incorporated into the structure of pasta. Glucose release is significantly reduced (DM basis, Figure 3) with the inclusion of inulin (with the exception of inulin at 10%). However, when available starch content within samples is taken into account, glucose release is increased (Figure 4). This may result from a loss of starch from pasta during the cooking process, possibly related to the higher cooking losses (Table 1) observed in inulin pasta products. This in turn may be related to the weakening of the starch–protein matrix in the overall pasta structure.

Guar inclusions into pasta product show a different mechanism for significantly reducing glucose release (grams per gram basis) and available starch. One hypothesis for this is that the guar encapsulates the starch granules in a protective coat, thus reducing the potential degradation of starch and overall glucose release (Table 2). The SEM images of both raw and cooked pasta products with guar (Figures 1 and 2) appear to support this hypothesis, with the starch granules being coated in a layer of guar gum. These results support those already observed by Brennan et al. (*19*) and Edwards et al. (*43*).

The main objective of this work was to better understand the mechanisms by which the addition of different types of dietary fibers in pasta affects its cooking quality, textural attributes, and starch degradation. These mechanisms are complex and could be not uniquely attributed to the structural and geometric characteristics of the protein network or to the

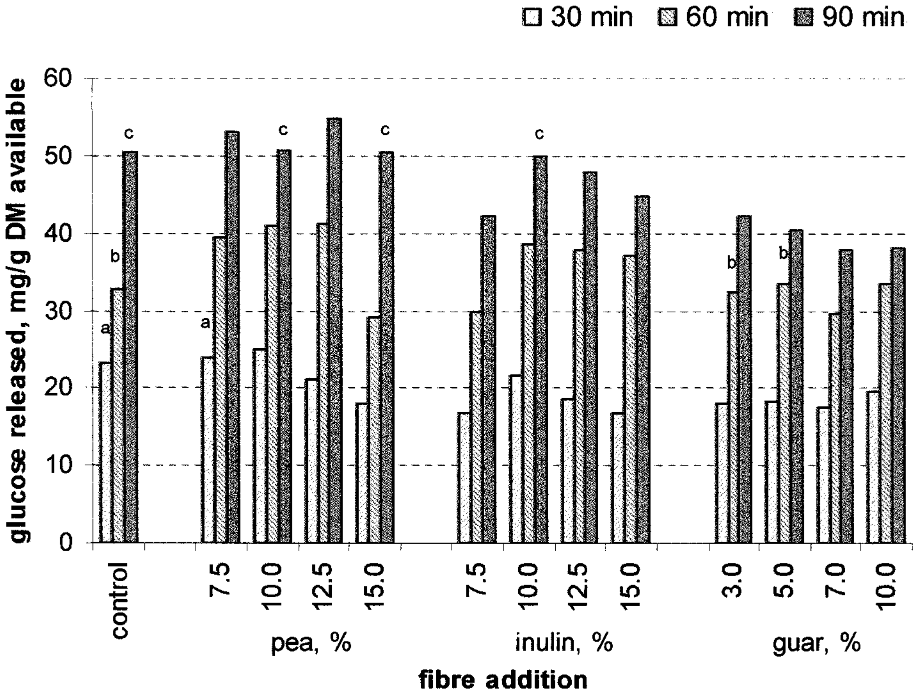


Figure 3. Glucose released by a unit of DM. Values labeled with the same letter are not significantly different ($P < 0.001$) from the control.

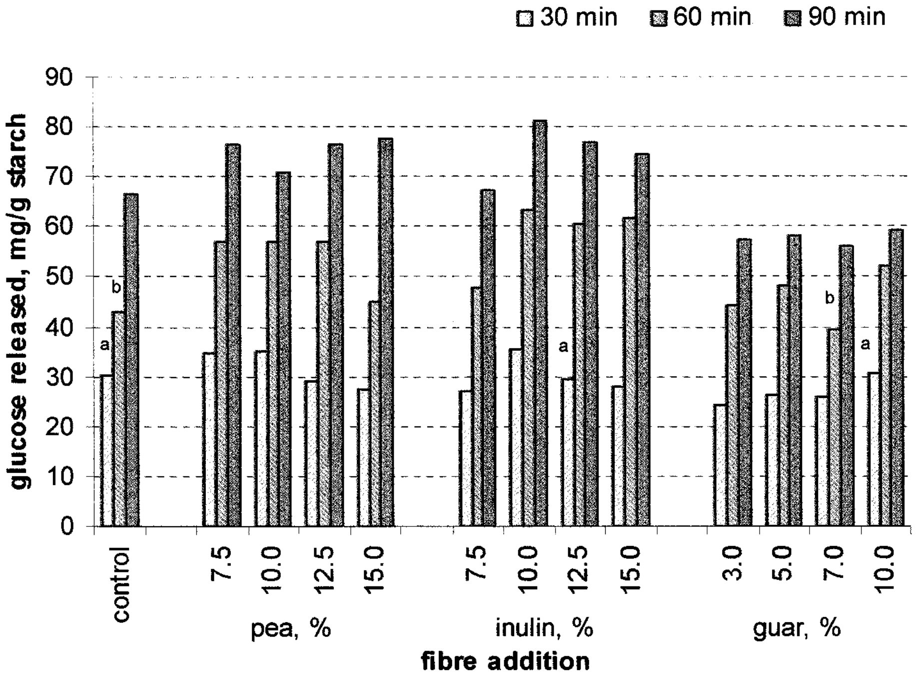


Figure 4. Glucose released by 1 g of starch available. Values labeled with the same letter are not significantly different ($P < 0.001$) from the control.

structural state of starch, but more likely to interaction between protein, starch, and fiber at the microscopic level (*17*).

Our results show that pasta texture, structure, cooking characteristics, and potential nutritional quality are intrinsically linked to the integration of fiber into pasta systems. As such, the incorporation of fiber significantly alters the quality attributes of the pasta products. Major differences in pasta structure may be related to the solubility of the fiber added. In particular, pea (mainly insoluble) and guar (soluble) fibers show marked differences in their potential to affect sugar release during in vitro digestibility studies. These differences may be attributed to the behavior of the fiber within the cooked pasta system and the relationship of the fiber with starch granules.

This study appears to confirm that the inclusion of insoluble dietary fiber into cereal products leads to a disruption of the protein matrix. Conversely, inclusion of soluble fiber, such as guar gum, results in the entrapment of starch granules within a viscous protein—fiber—starch network.

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