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# Effect of extrusion conditions on physicochemical and sensorial properties of corn-broad beans (*Vicia faba*) spaghetti type pasta

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ABSTRACT

Corn-broad bean spaghetti type pasta was made with a corn/broad bean flour blend in a 70:30 ratio, through an extrusion-cooking process (Brabender 10 DN single-screw extruder with a 3:1 compression ratio). The effect of temperature ($T = 80$, 90 and 100 °C) and moisture ($M = 28\%$, 31% and 34%) on the extrusion responses (specific consumption of mechanical energy and pressure) and the quality of this pasta-like product (expansion, cooking-related losses, water absorption, firmness and stickiness) was assessed. The structural changes of starch were studied by means of DSC and XRD. The extrusion-cooking process, at $M = 28\%$ and $T = 100$ °C, is appropriate to obtain corn-broad bean spaghetti-type pasta with high protein and dietary fibre content and adequate quality. The cooking characteristics and resistance to overcooking depended on the degree of gelatinisation and formation of amylose–lipid complexes. The critical gelatinisation point was 46.55%; beyond that point, the quality of the product declines.



## 1. Introduction

In wheat pasta, gluten plays a fundamental role in the formation and characteristics of the dough. Consequently, gluten is the main determining factor of the quality of this pasta during cooking (Bruneel, Pareyt, Brijs, & Delcour, 2010). Gluten-intolerant people must remove this component from their diet as the only effective treatment against the pathology (Cabrera-Chavez & Calderon de la Barca, 2010; Witczak, Korus, Ziobro, & Juszczak, 2010). This has prompted a number of research projects seeking to imitate gluten's viscoelastic properties, which has presented a new use for various non-conventional starches and flours such as manioc or cassava (Lorenzo, Zaritzky, & Califano, 2009; Sánchez, Osella, & De la Torre, 2002), quínoa (Chillo et al., 2009), amaranto (Chillo et al., 2010; Mariotti, Lucisano, Ambrogina Pagani, & Ng, 2009) among others.

The development of farinaceous gluten-free product is not a simple process, since it is necessary to create a matrix which is uniform and cohesive enough to bear the cooking process and confer quality attributes to the final product.

The traditional process used in the manufacturing of rice noodle, widely consumed in south-east Asia, involves numerous and laborious heating and cooling steps. In this process, at least a part of pregelatinised rice flour or starch is used, to be then mixed with the rest of the flour and water and, thus, form a three-dimensional network with viscoelastic characteristics (Tan, Li, & Tan, 2009).

The extrusion-cooking method represents an alternative technology that is adequate for the manufacturing of gluten-free pasta-like products (PLP), since it involves the unification of the pregelatinisation and formation steps (Amerayo, Gonzalez, Drago, Torres, & De Greef, 2011; Marti, Seetharaman, & Pagani, 2010; Sirirat, Charutigon, & Rungsardthong, 2005; Wang, Bhirud, Sosulski, & Tyler, 1999). In a gluten-free matrix, starch contributes substantially to the final structure and quality of the PLP. As it becomes part of a complex matrix, its modifications (gelatinisation, retrogradation, dextrinisation) and interactions with other components (starch-protein-lipid-polysaccharide) are promoted by the mechanical and thermal processes involved in manufacture (Marti et al., 2010). Such modifications allow for the formation of a continuous three-dimensional network of retrograded amylose and other structures, such as amylose–lipid complex crystals, that would stabilise the network, preventing the solubilisation of the material when the PLP is subjected to cooking (Amerayo et al., 2011; Marti, Pagani, & Seetharaman, 2011).

In order to improve the quality of gluten-free doughs, studies were carried out in which starches of different origins, gums, hydrocolloids and protein that are different from those of gluten and its combinations were incorporated (Lazaridou, Duta, Papageorgiou, Belc, & Biliaderis, 2007; Sánchez, González, Osella, Torres, & De la Torre, 2008; Witczak et al., 2010). However, it is possible to

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obtain PLP with adequate quality characteristics without the addition of gluten substitutes by exercising control in the formulation and variables of the extrusion process.

Most of the extruded gluten-free products found in the market include corn and rice as their main ingredient due to its abundance, low cost and high expansion capacity, as well as for being suitable for coeliacs. However, it is low in protein and dietary fibre content and quality. Leguminous flours are a good supplement for cereals because not only do they increase protein content but they also improve its biological value. The FAO thus recommends a 30:70 ratio of leguminous-cereal flours. However, the sensory characteristics of certain blends may be negatively affected in combinations following this ratio (Torres & Guerra, 2003).

The effect of adding flours from different leguminous crops such as *Glycine max* (Pérez et al., 2008), *Phaseolus vulgaris* (Anton, Fulcher, & Arntfield, 2009), *Cicer arietinum* (Lazou, Michailidis, Thymi, Krokida, & Bisharat, 2007), *Lathyrus annuus* and *Lathyrus clymenum* (Pastor-Cavada et al., 2011) to corn-based extruded products has been widely studied.

Broad beans (*Vicia faba*) have their origin in the East, and their consumption is popular in South America (Haciseferogullari, Gezee, Bahtiyarca, & Menges, 2003). Due to their great resistance to low temperatures, they are, among leguminous plants, the best adapted to the Andean region of the province of Jujuy, Argentina, and represent to the inhabitants of that region a source of energy, protein, folic acid, niacin, vitamin C, magnesium, potassium, iron and dietary fibre. Due to the high levels of lysine in their protein they are an adequate complement to the protein of cereals (Azaza et al., 2009; Chillo, Laverse, Falcone, & Del Nobile, 2008). According to Smith and Hardacre (2011), they have great potential in the snack food industry. Their addition to wheat pastas does not affect their sensory characteristics (Giménez, Drago, De Gree, Gonzalez, & Sammán, 2012; Petitot, Boyer, Minier, & Micard, 2010). However, there is scarce information about their use in blends destined for the formulation of gluten-free PLP.

The aim of this study was to obtain corn spaghetti type pasta fortified with 30% broad bean flour and to determine the effect of extrusion temperature and moisture on its physicochemical and sensory quality parameters.

## 2. Materials and methods

### 2.1. Raw materials

Corn flour was provided by Molinos Puerto Reconquista (Santa Fe, Argentina). Size was reduced using a Buhler-Miag roller mill, in order to obtain flour with a particle size between 0.191 and 0.490 mm.

Broad Beans (*Vicia faba*) were hulled manually and drying in solar dryer, were obtained from a Cooperative of producers (CAUQUEVA - Tilcara, Jujuy, Argentina) and ground using a fixed hammer mill (Retsch, Haan, Germany). Final particle size range was 150 to 560 μm. The ratio of corn/broad beans flours used was 70/30.

### 2.2. Extrusion-cooking – pasta-like (spaghetti-type) product elaboration

One hour before each extrusion experiment, a grits blend sample containing 70% cornflour and 30% broad bean (*Vicia faba*) flour was prepared using a planetary mixer (Brabender) and conditioned at the corresponding moisture by adding tap water. The blend samples were kept in a plastic bag until the extrusion step.

The extrusion process was carried out in a Brabender 10 DN single screw extruder, using a 3:1 compression ratio screw, a 1.5 mm × 3 (diameter × no. of holes) die and a screw speed of 60 rpm. The feeding rate of the extruder was at full capacity. While the extruder feeding section was maintained cool by circulating water through the jacketed device, the metering and die sections were both kept at the temperature corresponding to each run by using the heat control device of the extruder. Extrusion conditions, temperature ($T$) and flour moisture ($M$) were selected according an experimental design $2^3$, ($T$: 80, 90 and 100 °C; and $M$: 28%, 31% and 34%) with a triplicate central point. Samples were taken after the stationary flow was reached. Die pressure, torque and mass output were measured. Cooking loss (CL%), water absorption (WA), global sensorial score (GSS), specific mechanical energy consumption (SMEC), pressure (P) and expansion (E) were evaluated as responses.

The products were dried at 40 °C and 40% relative humidity for 16 h. The experiment was carried out in duplicate.

### 2.3. Chemical composition and dietary fibre

Raw materials and pasta were analysed for protein, fat, ash, and moisture using the standard procedures of AOAC (1995). Moisture was determined in a vacuum oven (SHE-LAB 1410), AOAC 925.09 method. Lipid content was determined according to the acid hydrolysis method, AOAC 922.06. Total protein content was determined using Kjeldahl (Büchi Digestion Unit K-435) procedure with a nitrogen-to-protein conversion factor of 6.25 (AOAC 984.13). Ash analysis used carbonisation in a muffle furnace at 550 °C (AOAC 923.03). Fibre was determined by enzymatic–gravimetric method (AOAC 985.19).

### 2.4. Specific mechanical energy consumption (SMEC) and pressure (P)

Pressure values (P) at the extruder die were obtained using a transducer (Dynisco, Franklin, MA). SMEC (J/g) was calculated according to the formula:

$$\mathrm{SMEC} = \frac{K\,T\,N}{Q}$$

where $T$ is torque in Brabender units; $N$ is screw speed in rpm and $Q$ is mass output in g/min.

### 2.5. Radial expansion (E)

Diameters (mm) were measured with a Vernier on ten pieces of sample, and radial expansion ($E$) was determined as the ratio $E = D \times d^{-1}$, where $D$ is the extruded diameter (average of 10 determinations) and $d$ is the die diameter.

### 2.6. Quality evaluation of corn-broad bean spaghetti type pasta

#### 2.6.1. Cooking time ($t_c$)

Ten-gram samples of the PLP were placed into a 500-ml beaker with 200 ml of boiling distilled water. Every 30 s, during cooking, the core strand of the spaghetti type pasta was examined by squeezing it between two transparent glass slides. The cooking time was determined as the time when the white core had disappeared.

#### 2.6.2. Cooking loss (CL) and water absorption (WA)

Ten grams of the PLP samples, 10-cm long approximately, were placed into a 500-ml beaker with 200 ml of boiling distilled water. After the required cooking time, the cooked product was drained 3 min and weighed to determine water absorption, reported as g of water/g of PLP (db). The cooking water was then collected in an aluminium vessel, placed into an oven at 105 °C and evaporated to dryness. The residue was weighed and reported as percentage of the starting material.

*2.6.3. Global sensorial score (GSS)*

Sensory evaluation was carried out with a trained panel of three persons to evaluate firmness and stickiness. The global score was obtained by consensus in two replications (Amerine, Pangborn, & Roessler 1965. Chap. 8).

A 0–5 scale was used. The 0 value was assigned for the firm and not sticky noodle and 5 for the most soft and very sticky one. A global score (firmness + stickiness) less than or equal to 5 was considered acceptable.

All analyses on cooked PLP (CL, WA and GSS) were made at optimal cooking time ($t_c$) and at overcooking time of $t_{c+10}$ min. For each time, five determinations were performed. Surface regression models for each response were determined at overcooking time ($t_{c+10}$ - min) because at this moment the stability of the structure is more evident.

*2.7. Structural modifications of starch*

Starch structure was evaluated using X-ray diffraction and differential scanning calorimetry (DSC) techniques. A Ciclotec mill (Tecator, Hoganas, Sweden) with a sieve of 1 mm was used to mill samples.

Differential scanning calorimetry (DSC)

The thermograms were obtained with a DSC Q200 TA. The instrument was calibrated with indium using an empty pan as reference. The sample preparation included weighing 2–3 mg of ground extrudates in a calibrated DSC pan. Distilled water was added to obtain a solids content of 25% in the mixture. The samples were heated from room temperature to 135 °C at a rate of 10 °C/min in the presence of nitrogen. Values of onset temperature ($T_o$), peak temperature ($T_p$) and enthalpy ($\Delta H$/g) were recorded for melting endotherms.

a) X-ray diffraction

Diffractograms were obtained with a Shimadzu DX-1 diffractometer (Shimadzu, Kyoto, Japan). The X-ray source was CUK$\alpha$ radiation The X-ray diffractometer was operated in reflection mode at 30 kV and 40 mA. Data were collected from 12° to 30° at scanning rate 1°/min.

The area of the three characteristic peaks corresponding to native starch structure (at $2\theta$ of 13°, 18° and 23°) was measured. Crystallinity % was expressed as the ratio of the sum of the areas corresponding to these peaks to total area.

*2.8. Statistical analysis*

The data were analysed and presented as average value ± standard deviation. Statistical differences between the average values were analysed using Tukey's HSD comparison test. A level of confidence of 95% ($p < 0.05$) was estimated. The program STATISTICA 5.0 for Windows (StatSoft Inc., Tulsa, OK) was used.

Surface response methodology was used to obtain surface regression models for each response as a function of extrusion temperature and flour moisture. Statgraphics plus for Windows version 5.1 (Statistical Graphics Corp., Herndon, VA) was used for the statistical analysis.

## 3. Results and discussion

*3.1. Raw materials – chemical composition*

Table 1 shows the nutrient content of corn and broad bean flours. Because broad bean flour has higher protein, dietary fibre and mineral content, it is an important supplement to corn flour. The substitution of corn with 30% broad bean flour increases the protein content, reaching values of about 15%, in accordance with the values recommended by FAO/OMS (1982). Such increase is similar to that obtained in bread wheat spaghetti fortified with broad bean (Giménez et al., 2012). However, the increase in the chemical score (results not shown) is greater when the cereal used in the blend is wheat, due to the tryptophan deficiency of corn.

The substitution of cornflour with 30% broad bean flour contributes a significant amount of dietary fibre (8.5%). Among the most common deficiencies of a gluten-free diet is that of dietary fibre, since gluten-free products are not usually enriched and they are generally manufactured with refined flour or starch. Thus, such diets do not always meet the 20–30 g/day recommended intake for dietary fibre (Stojceska, Ainsworth, Plunkett, & Ibanoglu, 2009). Consequently, the incorporation of broad bean flour to gluten-free farinaceous systems would contribute to the dietary fibre intake.

*3.2. Effect of extrusion temperature (T) and moisture content of flour blend (M) on the extrusion process and spaghetti type pasta quality*

Table 2 shows the values of the responses analysed during the extrusion process and of the quality of the final product: pressure (P), specific mechanical energy consumption (SMEC), expansion (*E*), cooking loss (CL) and global sensory score (GSS).

Tables 3 and 4 show the variance analysis and the regression models for each response analysed. According to these results, it can be observed that, in all responses, the linear terms of the regression model are significant ($p < 0.05$) and only in the mathematical models describing CL and GSS are the crossed terms $T \times M$ and the square term of $T$ significant ($p < 0.05$), respectively. In most of the cases the lack of fit was not significant ($p > 0.05$), which indicates that the models adequately explain the effect of temperature and moisture on these responses, except for E.

*3.2.1. Specific mechanical energy consumption (SMEC) and pressure (P)*

Fig. 1 shows that both SMEC and *P* tend to decrease as *T* and *M* increase, since higher temperatures facilitate the transformation from solid to viscoelastic flow and greater moisture produces a lubricating effect, resulting in less friction and, consequently, less transferred energy (Duarte, Carvalho, & Ascheri, 2009; Pérez et al., 2008).

According to González et al. (2007) and Ruiz-Ruiz et al. (2008), the degree of cooking (destruction of the granular and crystalline structure of starch) is favoured by the increase in SMEC. However, an increase in the extrusion temperature has a positive effect on gelatinisation and is greater as moisture increases. Amerayo et al. (2011) states that the effect of temperature and moisture on the degree of cooking will depend on the particular level of each.

Pressure displays the same behaviour as SMEC. For the same moisture level, there is a direct connexion between SMEC and P, which is in line with the findings of González, Torres, and De Greef (2006).

Both the SMEC and P values are lower than those found in corn PLP with different endosperm hardness levels (Amerayo et al., 2011) extruded under similar conditions. This could be due to a decrease in the level of friction as a consequence of the higher protein and fibre content contributed by broad bean flour, which may produce a discontinuity in the structure formed, causing flow viscosity to decrease. This behaviour is similar to that reported by Duarte et al. (2009) and Onwulata and Konstance (2006) for corn extruded products with high protein and dietary fibre.

*3.2.2. Radial expansion (E)*

The expansion produced in the PLP spaghetti-type (Fig. 2) tends to increase as temperature increases and moisture content de-

**Table 1**
Proximate composition of flours and flour blend (g/100 g db).

| Flours | Protein | Lípids | Ash | Fibre | HC* |
|---|---|---|---|---|---|
| Broad bean (B) | $31.07 \pm 0.13$ | $2.66 \pm 0.09$ | $3.99 \pm 0.09$ | $20.01 \pm 1.85$ | 42.26 |
| Corn (C) | $6.48 \pm 0.21$ | $0.64 \pm 0.01$ | $0.36 \pm 0.02$ | $1.98 \pm 0.34$ | 90.54 |
| C/B 70:30 | $14.71 \pm 0.35$ | $1.32 \pm 0.06$ | $1.55 \pm 0.09$ | $8.50 \pm 0.62$ | 73.92 |

Each point corresponds to the average value of four independent determinations.
* HC: Carbohydrates, estimated by difference.

**Table 2**
Response values corresponding to each extrusion condition (temperature and moisture content) according to experimental design ($3^2$).

| Extrusion conditions $T$ (°C)–$M$ (%) | P ($10^5$ Pa) | SMEC (J g$^{-1}$) | $E$ | WA $t_c$ (g $H_2O$/g PLP) | WA $t_{c+10}$ (g $H_2O$/g PLP) | CL $t_c$ (%) | CL $t_{c+10}$ (%) | GSS ($t_c$ min) | GSS ($t_{c+10}$ min) |
|---|---|---|---|---|---|---|---|---|---|
| 80–28 | $121.85 \pm 4.14^{a}$ | $107.68 \pm 4{,}12^{a}$ | $1.00 \pm 0.02^{a}$ | $2.53 \pm 0.03^{ac}$ | $3.52 \pm 0.04^{af}$ | $12.34 \pm 0.09^{a}$ | $17.97 \pm 0.34^{a}$ | 7 | 6 |
| 80–31 | $78.09 \pm 5.80^{bd}$ | $65.92 \pm 7.76^{b}$ | $0.96 \pm 0.02^{b}$ | $2.49 \pm 0.02^{ac}$ | $3.57 \pm 0.07^{ab}$ | $14.46 \pm 0.46^{b}$ | $26.11 \pm 0.13^{b}$ | 8 | 10 |
| 80–34 | $66.93 \pm 1.71^{be}$ | $42.42 \pm 2.18^{c}$ | $0.89 \pm 0.03^{c}$ | $2.98 \pm 0.31^{b}$ | $3.97 \pm 0.11^{cd}$ | $16.33 \pm 0.64^{c}$ | $34.80 \pm 0.26^{c}$ | 10 | 10 |
| 90–28 | $86.38 \pm 2.62^{d}$ | $94.93 \pm 4.00^{ad}$ | $1.02 \pm 0.01^{a}$ | $2.45 \pm 0.04^{ac}$ | $3.69 \pm 0.04^{bcf}$ | $10.46 \pm 0.14^{d}$ | $15.67 \pm 0.03^{d}$ | 3 | 4 |
| 90–31* | $62.35 \pm 1.99^{ce}$ | $55.41 \pm 3.41^{c}$ | $0.98 \pm 0.02^{bd}$ | $2.62 \pm 0.07^{a}$ | $3.85 \pm 0.11^{bc}$ | $10.90 \pm 0.32^{d}$ | $17.49 \pm 0.35^{a}$ | 7 | 8 |
| 90–31* | $60.36 \pm 1.25^{ce}$ | $58.15 \pm 4.85^{c}$ | $0.98 \pm 0.03^{bd}$ | $2.59 \pm 0.05^{a}$ | $3.70 \pm 0.18^{bc}$ | $9.76 \pm 0.43^{d}$ | $16.97 \pm 0{,}43^{a}$ | 10 | 9 |
| 90–31* | $62.21 \pm 1.48^{ce}$ | $56.78 \pm 5.44^{c}$ | $0.97 \pm 0.03^{bd}$ | $2.66 \pm 0.09^{a}$ | $3.89 \pm 0.24^{bc}$ | $11.18 \pm 0.23^{d}$ | $18.12 \pm 0.21^{a}$ | 9 | 8 |
| 90–34 | $50.34 \pm 0.99^{f}$ | $22.00 \pm 2.90^{ec}$ | $1.02 \pm 0.03^{b}$ | $3.47 \pm 0.03^{d}$ | $4.20 \pm 0.17^{d}$ | $13.86 \pm 0.26^{b}$ | $21.12 \pm 1.43^{e}$ | 10 | 10 |
| 100–28 | $74.37 \pm 2.62^{bde}$ | $81.60 \pm 1.56^{d}$ | $1.17 \pm 0.01^{e}$ | $2.13 \pm 0.05^{e}$ | $2.99 \pm 0.07^{e}$ | $9.07 \pm 0.23^{e}$ | $11.14 \pm 0.26^{f}$ | 2 | 3 |
| 100–31 | $45.19 \pm 5.75^{f}$ | $75.28 \pm 1.25^{bd}$ | $1.01 \pm 0.02^{a}$ | $2.27 \pm 0.05^{ce}$ | $3.31 \pm 0.12^{ae}$ | $10.64 \pm 0.35^{d}$ | $12.08 \pm 0.34$f | 3 | 4 |
| 100–34 | $37.76 \pm 2.97^{f}$ | $24.23 \pm 1{,}19^{e}$ | $0.99 \pm 0.02^{ad}$ | $2.67 \pm 0.11^{a}$ | $3.68 \pm 0.05^{bcf}$ | $12.92 \pm 0.46^{a}$ | $15.55 \pm 0.12^{d}$ | 4 | 6 |

Each point corresponds to the average value ± standard deviation of four independent determinations. Different letters for each column indicate significant differences ($P < 0.05$).
* corresponding to centrals points; P: pressure, SMEC: specific mechanical energy consumption, E: expansion; WA $t_c$: water absorption to cooking time; WA $t_{c+10}$: water absorption to overcooking time; CL $t_c$: cooking loss to cooking time; CL $t_{c+10}$: cooking loss to overcooking time; GSS $t_c$: global sensorial score to cooking time, GSS $t_{c+10}$: global sensorial score to overcooking time.

creases; these values were lower than those found by Wang et al. (1999) and Wójtwicz & Móscicki, 2009) in pasta-like product from pea flour and precooked wheat PLP, respectively.

Expansion is governed by two factors: the viscosity of the dough (high $T$ and $M$) and the elastic strength of the extruded dough (low $T$ and $M$) (Ding, Ainsworth, Tucker, Marson, & Plunkett, 2006). In the extrusion temperature and moisture ranges used in this study, no important differences were obtained between the pressure generated by the nozzle and the atmospheric pressure, which is the driving force for the growth of the bubble. Therefore, under these conditions, viscosity dominates expansion.

Moisture content was the main factor affecting expansion. An increase in the extrusion temperature caused the flow viscosity to decrease, favouring expansion.

SMEC, P and E display the same behaviour; for this reason, greater degree of cooking and pressure positively affect elasticity, and, consequently, the expansion of the pasta-like product. According to Ruiz-Ruiz et al. (2008), a higher degree of gelatinisation is associated with greater expansion.

*3.2.3. Cooking loss (CL), water absorption (WA) and global sensory score (GSS)*

Cooking losses, water absorption, firmness and stickiness of the PLP are indicators of the stability of the retrograded starch network formed. The optimum cooking times ($t_c$) of the corn-broad bean spaghetti type pasta obtained at the various extrusion conditions were in the range of 8–13 min. The longest $t_c$ corresponded to the samples with the best sensory attributes.

Cooking-related losses in the product increase, and the quality of their sensory attributes (firmness and stickiness) diminishes as moisture increases and extrusion temperature decreases. These characteristics are intensified under overcooking conditions ($t = t_{c+10}$ min). At $t = t_c$, cooking losses do not exceeded 12.5%, except when the extrusion humidity reaches 34%. Although the determined values exceed the considered acceptable range for semolina spaghetti (7–8%) (Doxastakis et al., 2007) and starch noodles (9–10%) (Tan et al., 2009), they are lower than those reported by Sirirat et al. (2005) for commercial noodles.

Cooking losses are similar to those found in gluten-free spaghetti with a base of amaranthus flour (Chillo, Laverse, Falcone, & Del Nobile, 2007) and extruded rice noodles (Marti et al., 2010; Sirirat et al., 2005), and lower than those found by Wang et al. (1999) in PLP from pea flour. However, they are higher than those found by Amerayo et al. (2011) in corn PLP. This behaviour may be due to the higher fibre content contributed by broad bean flour, which might lead to the weakening of the starch network formed (Duarte et al., 2009; Pai, Blake, Hamaker, & Campanella, 2009).

Fig. 3a and b show that CL and GSS presented acceptable values ($CL < 12.5\%$ and $GSS \leqslant 5$) when the extrusion temperature was 100 °C and the blend moistures 28% and 31%, which suggests that higher temperatures and lower moisture contents in the extrusion-cooking process allow for the creation of a more continuous and less soluble structure. The hydration properties during cooking will not only depend on the damaged and gelatinised starch but also on the resistance offered by the structures formed during extrusion.

Fig. 3c shows that the corn-broad bean spaghetti-type pasta obtained at 100 °C with 28% and 31% moisture presents greater restriction to water absorption (WA) during cooking. This behaviour can be attributed to the formation of new structures such as retrograded amylose and amylose–lipid complexes which favour the structural stability of PLP, providing greater resistance to hydration with low loss of solids during overcooking (Amerayo et al., 2011; Marti et al., 2011).

At an extrusion temperature of 80 °C and 28% moisture, the WA presented by the PLP during cooking is also low. However, the cooking-related losses are high, which suggests a reduction in the formation of stabilising structures of the starch network and a lower degree of gelatinisation.

According to Marti et al. (2010), other polysaccharides might also be involved in the starch network, which would favour gluten-free PLP firmness. According to Repo-Carrazco-Valencia, Peña, Kallio, & Salminem, 2009), and Tudorica, Kuri, & Brennan,

**Table 3**
Degree of significance ($p$ values) of the polynomial regression model coefficients, corresponding to each response.

| Response | Source of variation (model term) | | | | | |
|---|---|---|---|---|---|---|
| | $M$ | $T$ | $M^2$ | $MT$ | $T^2$ | Lack of fit |
| P ($10^5$ Pa) | 0.0063 | 0.0097 | 0.2344 | 0.0811 | 0.9764 | 0.2423 |
| SMEC (J $g^{-1}$) | 0.0005 | 0.0038 | 0.4137 | 0.1387 | 0.0209 | 0.6039 |
| E | 0.0026 | 0.0021 | 0.0102 | 0.0110 | 0.0708 | 0.0099 |
| CL $t_{c+10}$ (%) | 0.0064 | 0.0030 | 0.3588 | 0.0193 | 0.0822 | 0.2071 |
| WA $t_{c+10}$ (g $H_2O$/g PLP) | 0.0050 | 0.0149 | 0.1142 | 0.2896 | 0.0060 | 0.7030 |
| GSS $t_{c+10}$ | 0.0194 | 0.0238 | 0.0538 | 0.1217 | 0.0023 | 0.3061 |

P: pressure, SMEC: specific mechanical energy consumption, E: expansion, CL $t_{c+10}$: cooking loss to overcooking time; WA $t_{c+10}$: water absorption to overcooking time, GSS $t_{c+10}$: global sensorial score to overcooking time.

**Table 4**
Regression model corresponding to each response.

| Response | Regression model | $R^2$ |
|---|---|---|
| P ($10^5$ Pa) | $1602.09 - 9.0978\,T - 64.7165\,M$ | 0.9556 |
| SMEC(J $g^{-1}$) | $1492.94 - 5.02629$ T $- 60.5206$ M | 0.9982 |
| CL $t_{c+10}$ (%) | $-42.97 - 0.69\,T + 6.32$ M $- 0.10$ TM | 0.9761 |
| WA $t_{c+10}$ (g $H_2O$/g PLP) | $-10.14 - 0.61\,T - 0.62\,M - 0.004\,T^2$ | 0.9668 |
| GSS $t_{c+10}$ | $-186.97 + 3.32\,T + 2.81$ H $- 0.015\,T^2$ | 0.9259 |

2002, the greater physical stress produced as extrusion temperature increases and moisture decreases could reduce the amount of insoluble fibre and increase that of soluble fibre. Such increase has a positive impact on the structure of this type of product. Petitot et al. (2009) have suggested that the formation of protein aggregates during the drying process of the wheat pasta can improve hardness, elasticity and cohesion. Along the same lines, Giménez et al. (2012) determined that enriching bread-wheat flour with 30% broad bean flour does not affect the texture and physicochemical properties of spaghettis, since a higher protein content plays an important role in the stabilisation of the protein-polysaccharide matrix.

### 3.3. Thermal analysis and RX diffraction

The thermal properties of the raw material and extruded PLP are shown in Table 5. In non-extruded flours and blends, two endotherms are observed: one ($E_G$) that can be associated with the gelatinisation of starch and another one ($E_2$) with a peak between 90 and 95 °C, corresponding to the denaturation of protein and/or the dissociation of the amylose–lipid complex type 1, which are naturally present in flours (Putseys, Lambert, & Delcour, 2010).

The PLP thermograms showed four endotherms: the first one, $E_1$, between 42 and 52 °C, corresponding to retrograded amylopectin (Liu, Yu, Chen, & Li, 2007), $E_G$, and two more corresponding to the so-called "V" structure, characteristic of amylose–lipid complexes ($E_2$, type 1 and $E_3$, type 2) as found also by Amerayo et al. (2011) in corn spaghetti-type pasta.

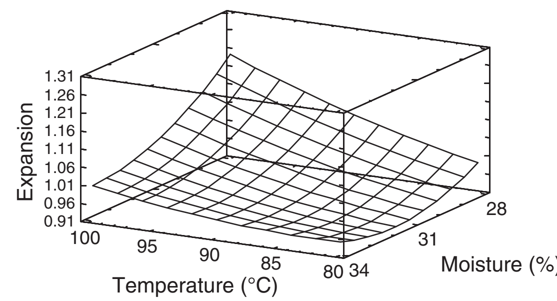


**Fig. 2.** Surface responses obtained for expansion, corresponding to corn-broad bean spaghetti-type pasta.

In the extruded samples, the gelatinisation temperature ($T_{pG}$) increases with the extrusion temperature and moisture, and the gelatinisation range decreases, with respect to the non-treated blends, from 22.58 to 12.54 °C, which indicates that residual starch granules after extrusion are more stable under heating conditions. According to Hormdok and Noomhorm (2007), starch treatments at high temperatures with low moisture levels result in greater homogeneity in the fusion of starch crystals, swelling and hydration. The degree of gelatinisation produced during the extrusion-cooking process increases as extrusion temperature and moisture increases, reaching a value of 81.16%. Fig. 4 shows the connexion existing between CL and GSS and the degree of gelatinisation (G) reached during the extrusion process. These quality characteristics in cooked PLP improve as the degree of gelatinisation increases, until they reach a critical point of gelatinisation (46.55%), beyond which quality declines.

Between 95 and 125 °C, endotherms $E_2$ and $E_3$ are observed, corresponding to the fusion of the type 1 and type 2 amylose–lipid complexes respectively. Type 1 complexes are formed at low temperatures (60 °C) and the nucleation speed is very high, resulting in a structure with little crystalline order and a dissociation temperature between 95 and 105 °C. On the other hand, Type 2 complexes show a higher formation temperature (90 °C). Their formation may

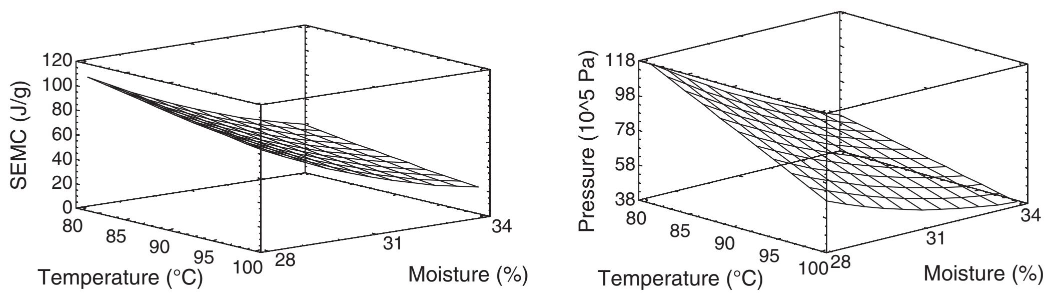


**Fig. 1.** Surface responses obtained for specific mechanical energy consumption and pressure, corresponding to corn-broad bean spaghetti-type pasta.

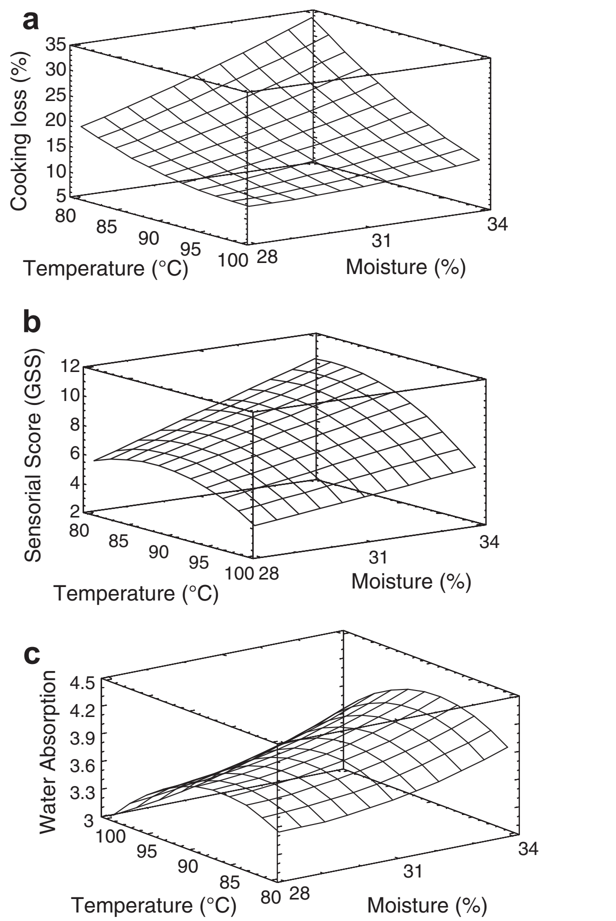


**Fig. 3.** Surface responses obtained for cooking loss (a), global sensorial score (b) and water absorption (c), corresponding to corn-broad bean spaghetti-type pasta.

be favoured in slow cooling and drying conditions, resulting in structures with perfectly defined crystalline regions that fuse at temperatures higher than 100 °C (Gelders, Vanderstukken, Goesaert, & Delcour, 2004; Putseys et al., 2010).

As extrusion moisture increases, the formation of amylose–lipid complexes decreases (decrease in enthalpy of fusion, $\Delta H_2 + \Delta H_3$). According to De Pilli et al. (2008) crystalline amylose–lipid complexes form when the temperature of the material is between its fusion ($T_m$) and glass transition ($T_g$) temperature. Water acts as a plasticiser during extrusion and the decrease in moisture content increases the $T_m$ and $T_g$ temperatures of the material. If the extrusion moisture allows for the temperature of the material to fall below $T_m$, crystallisation begins in the extruder.

Fig. 5 shows the connexion between CL and GSS and the formation of amylose–lipid complexes. It can be observed that the best textural (firmness + stickiness) and physicochemical characteristics of the pasta-like (spaghetti-type) product correspond to the extrusion conditions, which allowed for greater formation of the amylose–lipid complex.

Fig. 6 shows the diffractograms of non-extruded flours, PLP extruded at 100 °C and 28% of moisture, and a control sample (100% corn) obtained under the same conditions.

All of the samples present the three characteristic peaks of native starch (2$\Theta$: 15, 18 and 23) (Huang, Lu, Li, & Tong, 2007) and only in the extruded samples do two peaks appear (2$\Theta$: 13 and 20), which confirms the formation of the amylose–lipid complex (De Pilli et al., 2008; Marti et al., 2011; Zaidul, Yamauchi, Matsu-ura-Endo, Takigawa, & Noda, 2008).

In the control pasta-like sample, a marked reduction of the peaks 2$\Theta$: 15, 18 and 23 is observed. There is practically no native structure; thus, the percentage of total crystallinity (25.6%) may correspond to a greater extent to the formation of amylose–lipid complexes, amylose and retrogradated amylopectin. In corn-broad bean spaghetti-type pasta, the areas corresponding to the native structure of starch are greater than in the control sample. This

**Table 5**
Thermal analysis of raw material, flour blend and extruded PLP.

| Flours | $E_1$ | | $E_G$ | | | | | $E_2$ | | $E_3$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $T_{p1}$ | $\Delta H_1$ | $T_{oG}$ | $T_{pG}$ | $T_{fG}$ | $\Delta H_G$ | G (%) | $T_{p2}$ | $\Delta H_2$ | $T_{p3}$ | $\Delta H_3$ |
| Corn | | | 62.94 | 72.3 | 80.0 | 5.35 | | 94.87 | 0.79 | | |
| Broad bean | | | 59.25 | 67.02 | 76.0 | 4.46 | | 93.36 | 2.59 | | |
| C/B 70:30 | | | 59.92 | 72.98 | 82.5 | 4.78 | | 94.51 | 1.87 | | |
| PLP $T$(°C)–$M$(%) | | | | | | | | | | | |
| 80–28 | | | 66.61 | 72.08 | 84.5 | 3.41 | 28.66 | | | | |
| 90–28 | | | 67.82 | 72.42 | 83.9 | 3.40 | 28.89 | 93.00 | 0.31 | | |
| 100–28 | 50.19 | 0.48 | 69.56 | 73.51 | 85.0 | 2.55 | 46.55 | 93.05 | 0.74 | 120.00 | 1.67 |
| 100–31 | 52.93 | 0.64 | 70.35 | 74.84 | 84.6 | 2.52 | 47.29 | 94.85 | 0.23 | 124.00 | 1.64 |
| 100–34 | 52.61 | 0.90 | 72.46 | 77.02 | 85.0 | 0.90 | 81.16 | 94.25 | 0.15 | 115.80 | 0.81 |

$T_o$: onset temperature (°C); $T_P$: peak temperature (°C); $T_f$: end temperature (°C); $\Delta H$: enthalpy (J/g).
G (%): gelatinisation degree = 100 − ($\Delta H_{G\ PLP\ (T°,H\%)} \times 100/\Delta H_{G\ flour\ blend}$).
Each value corresponding to mean of three replications.

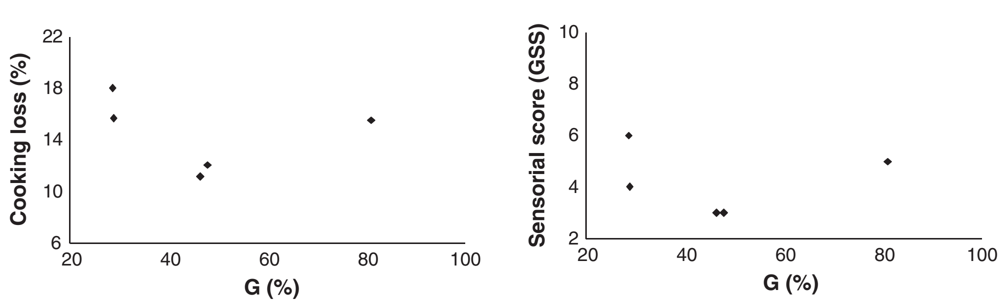


**Fig. 4.** Cooking loss and global sensorial score *versus* the gelatinisation degree (G).

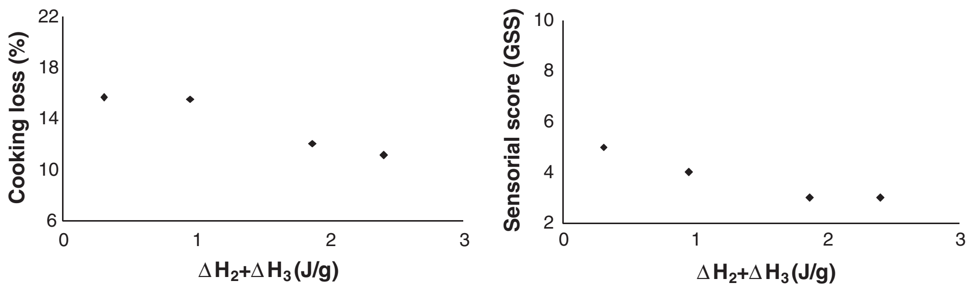


**Fig. 5.** Cooking loss and global sensorial score *versus* the dissociation energy from amylose–lipids complex ($\Delta H_2 + \Delta H_3$).

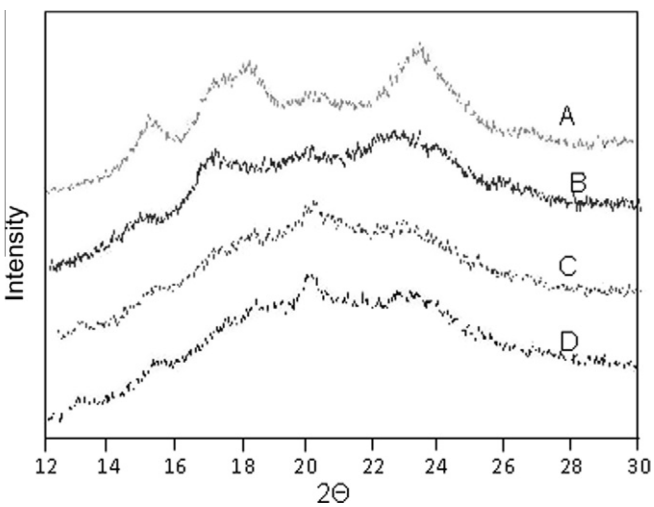


**Fig. 6.** X-ray diffraction patterns of corn flour (A), broad bean flour (B), corn spaghetti type pasta (C) and corn-broad bean spaghetti-type pasta (D) extruded at $T = 100$ °C and $M = 28\%$.

might be a consequence of the fact that an important portion of native starch in leguminous flours is encapsulated by cell walls that make its hydration and later gelatinisation difficult (Granito, Torres, & Guerra, 2003). The higher degree of total crystallinity (28%) in PLP containing broad bean flour corresponds both to native starch and to the new crystals formed. According to these results, during the extrusion process, the 70:30 corn/broad bean blend loses approximately 20% of total crystallinity. This percentage is enough to confer adequate cooking quality to the pasta-like spaghetti type. According to Amerayo et al. (2011), in good quality corn PLP the percentage of loss of native starch crystallinity is approximately 50%.

## 4. Conclusion

The extrusion-cooking process proves to be a useful technology for manufacturing corn-broad bean spaghetti-type pasta with adequate quality characteristics. The corn/broad bean complementation enhances the protein and dietary fibre content in the blend. Extrusion cooking at 100 °C and 28% moisture is appropriate to obtain pasta with adequate physicochemical and textural characteristics.

The textural properties of pasta-like spaghetti type and their behaviour during overcooking depend on the degree of gelatinisation reached during the extrusion-cooking process and the formation of the amylose–lipid complex. The critical point of gelatinisation, beyond which the quality characteristics of the product decline, was 46.55%.

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