Effect of Ingredients on the Quality of Gluten-Free Sorghum Pasta

Pablo Martín Palavecino, Mariela Cecilia Bustos, María Belén Heinzmann Alabí, Melani Solange Nicolazzi, María Cecilia Penci, and Pablo Daniel Ribotta

Abstract: Sorghum is an underutilized cereal in human food production, despite its flour being a potential gluten-free (GF) source in the development of several foods. Thus, the aim of the present investigation was to evaluate the effects and interactions of different ingredients on cooking quality and texture of GF pasta. Egg albumen (A), egg powder (E), xanthan gum (X), and pregelatinized corn starch (P) were used as ingredients, and Box-Behnken experimental design was applied to study the effects of these ingredients on pasta cooking behavior, color, and texture attributes. Responses were fitted to a second order polynomial equation, and multivariable optimization was performed using maximization of general desirability. Next, optimal formulations were validated, compared with two commercial gluten-free pastas by sensory evaluation, and finally, an industrial assay was carried out. Regression coefficients indicated that A and P improved cooking properties while A and E contributed the most to improving the pasta textural properties. As, X and P effects varied depending on the kind of sorghum flour used, the optimal formulations levels were different, but in both cases these models were satisfactory and capable of predicting responses. The industrial assay was carried out with white sorghum flour because it showed a higher acceptability in the sensory evaluation than brown sorghum flour pasta. This industrially made pasta resulted in slightly better cooking properties than the laboratory produced one, with the formulation adapting well to the conventional wheat pasta industrial process. Gluten-free sorghum pasta was produced, showing good cooking and textural properties and being a suitable option for gluten-sensitive individuals.

Keywords: gluten-free pasta, industrial assay, sensory evaluation, sorghum flour

Practical Application: With the aim to give gluten-sensitive individuals a new and better food alternative, gluten-free pasta was made from sorghum flour reaching good cooking and textural properties throughout the study of ingredients effect. Then, this pasta was produced at industrial scale showing that the formulation was a suitable option for producers.

Introduction

Celiac disease is an autoimmune disorder induced by the intake of foods containing certain proteins with properties only found in cereals such as wheat, barley, rye, kamut, spelt, and triticale. While there is a rising demand of gluten-free (GF) products, due to the growing number of celiacs and individuals who chose not to eat gluten-based products (Bustos and others 2015). It is difficult to produce good quality gluten-free (GF) foods such as pasta, cookies, and bread without the technological properties provided by gluten (Green and Cellier 2007; Sciarini and others 2012).

Although, the most used cereal flours for GF pasta production are rice and corn, there are many cereals and tubers capable of performing a useful role. For example, sorghum grain (*Sorghum bicolor (L.) Moench*) is rich in starch and polyphenolic compounds, and has already shown good results in the production of many types of foods, but its potential as an ingredient in the human diet has not yet been fully exploited. This cereal is usually grown in semi-arid regions, but its agronomic characteristics allow it to be cultivated in various climate, which makes it the fifth most produced cereal in the world (Suhendro and others 2000; Liu and others 2012; Palavecino and others 2016).

Pasta is a key element in the basic diet of most cultures; and is consequently one of the most consumed foods in the world, with the market presence of GF pasta being important for coeliac health. There are various types of pasta, with dried pasta being convenient because they are easy to store, prepare and serve. Consumer acceptance of cooked pasta is based primary on texture properties, but unfortunately, GF pasta tends to be sticky, generates a lot of cooking residue and has an unpleasant texture (Marti and Pagani 2013). Thus, in order to improve these properties, ingredients from several different sources are currently being investigated, such as native and modified starches, GF flours, gums, whey, and egg proteins (Kahlon and others 2013).

The enormous number of variables and their combinations involved in the development of a product generates problems to improve its properties, especially when considering that the improvement of one property is often detrimental to another. Thus, experimental design techniques provide an efficient means to optimize processing, incomplete factorial designs can be used to model the main effects and simple interactions, while at the same time reducing the amount of measurement points without losing fidelity and also providing the possibility of data regression.

Some attempts have been made to use sorghum flour in GF pasta. Suhendro and others (2000) optimized the processing

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parameter to produce 100% sorghum noodles by studying the preheating of flour+salt+water dough using a hotplate or a microwave oven, and found that finer flour, and the microwave method produced better quality noodles. Liu and others (2012) characterized four sorghum hybrids and evaluated their behavior on Chinese egg noodle quality, concluding that it was possible to manufacture a Chinese egg noodle with good physical attributes. In another study, Ferreira and others (2016) analyzed various mixtures in the development of gluten-free pasta, and found that the best results were obtained by mixing sorghum flour, rice flour and potato starch.

Although the above results are encouraging, no optimization of ingredient proportion was carried out in these studies and knowledge of the precise influence of ingredients/additives on the cooking and textural properties of sorghum pasta is essential for the development of good quality products. Thus, the aim of the present investigation was to determine the main effects and interactions of different ingredients on the GF cooking quality and pasta texture, in order to obtain good quality GF pasta using sorghum flour.

Materials and Methods

Materials

Sorghum flours were produced by Amylum S.A. (Córdoba, Argentina), through decortication of sorghum grains with a vertical dehuling device until 10% of weight loss and milled in an industrial hammer mill in order to obtain white and brown sorghum flour (WSF and BSF, respectively).

The following food grade ingredients were purchased from local supplier (Nicco S.R.L., Córdoba, Argentina): pregelatinized corn starch (P) (Ingredion, Argentina), xanthan gum (X) (Deosen Biochemical Corporation Ltd., China), egg powder (E) (Tecnovo S.A., Argentina), and egg albumen (A) (Tecnovo S.A., Argentina).

Sorghum flour properties

A proximate analysis of WSF and BSF was performed according to standard methods of AOAC (2000) (moisture: method 925.10; ash: method 923.03; lipid: method 920.39 and protein: method 920.87). Particle size distribution was determined using a Ro-Tap type sieve shaker (EJR 2000, Zonytest) and 200, 140, 100, 70, 40, 30, and 20 mesh sieves according to AOAC (2000) (method 965.22). Pasting properties were determined using a Rapid Visco Analyser (RVA 4500, Newport Scientific, Australia) using the RVA Standard Pasting Method (Newport Scientific Pty. Ltd., Warriewood, Australia). The pasting temperature (PT), peak viscosity (PV), peak time, hot paste viscosity (TV), final viscosity (FV), breakdown (BD), and setback (SB) were obtained from pasting curves.

Experimental design

A Box-Behnken Design (BBD) was selected for studying the ingredient behavior in a very precise way over a relatively small region (Ferreira and others 2007) with the maximum factor levels (ingredients) being established in preliminar experiments in order to guarantee easy dough handling (Table 1). In this sense, the maximum P content was limited because a large amount of this ingredient generates a highly viscous dough that causes problems in the extrusion process (Marti and Pagani 2013), and for the X content the limits established by *Codex Alimentarius* regulation were considered. The BBD used for each sorghum flour consisted of 27 formulations including 3 center points in random order, and the model response determination (cooking and texture properties) and process variables are explained bellow.

Table 1–Experimental design levels of selected variables.

		Level (g/100 g)		
Variable	Factor	Low	Middle	High
Xanthan gum	X	0	1.25	2.50
Egg albumen	A	0	5.50	11.00
Egg powder	E	0	4.50	9.00
Pregelatinized starch	P	0	15.00	30.00

Pasta preparation

The processing conditions are critical for ensuring good texture and cooking behavior (Marti and Pagani 2013). Here, the pasta was prepared with a domestic extruder pasta machine (FP 4070, ATMA, Argentina) as follows. First, dry ingredients (50 g) with an appropriate amount of water for each sample (about 20 mL, based on dough consistency) were mixed for 3 min in the corresponding bowl. Once the dough was obtained, it was forced to pass into the extruder cavity equipped with a spaghetti die of 2 mm diameter. The extrusion step was performed three times in order to improve the quality and homogeneity, according to Suhendro and others (2000). Finally, the pasta was manually cut into 150-mm-long pieces and dried in 2 stages, first at 40 °C for 30 min with forced air circulation oven without humidity control (Model 600 D060602, Memmert, Germany) and later at 45 °C and 75% relative humidity in pasta drier (CDH4060, FAC, Argentina) for 17 h according to Bustos, Perez, and Leon (2011).

Cooking properties

The optimal cooking time (OCT) was determined by the disappearance of the opaque line in the center of the pasta by the AACC Method 16 to 50 (AACC 2000). The dried pasta was cut into 40 mm strands to obtain 4 g of sample and placed in 200 mL of boiling distilled water. The OCT was determined by compressing a pasta sample between 2 glass slides and observing the line disappearance by taking samples at intervals of 1 min.

The GF pasta cooking properties were determined according to methods proposed by Tudorică and others (2002). Water absorption (WA) of the pasta was determined as the weight difference between the cooked pasta at OCT and raw pasta expressed as percentage of raw pasta, with the swelling index (SI) determined as the weight difference between the cooked pasta at OCT and the dried cooked pasta at 105 °C. Cooking loss (CL) was determined by evaporation of the cooking water contained in a preweighed beaker, to constant weight at 105 °C, the residue was expressed as g of solids/100 g of raw pasta. The reported values were the average of at least two replicates for each sample.

Texture analysis

Firmness, chewiness (product of hardness, cohesiveness and springiness) and adhesiveness of the cooked pasta were determined using a texture analyzer (Universal Testing Machine model 3342, Instron, U.S.A.) equipped with a load cell of 500 N coupled to a 25-mm-diameter cylinder probe. Samples were cooked until the OCT and 4 pieces of 50 mm were placed on the platform. At least four replicates were performed for each sample. The texture profile analysis (TPA) test was carried out according to Tudorică and other (2002) at a test speed of 50 mm/min and a trigger force of 0.05 N, the assay consisting of 2 compression cycles at 30% of the original height. Bluehill $2^{®}$ software for Windows (Instron, U.S.A.) was used for instrument operation and data collection.

Color determination

The color parameters of the flour and pasta were measured using a colorimeter (CM600d, Konica-Minolta) with a 10° observer inclination and D65 light. Approximately 3 g of flour were placed on a white flat surface and covered with 0% reflectance glass, with a colorimeter then positioned at the center of the glass to take measurements. Color determination of the cooked pasta was performed according to a standard method (14 to 22, AACC, 2000): four pasta strands of 50 mm were arranged in parallel over a white background and the colorimeter was lightly placed over the samples to collect data. Both these procedures were performed in triplicate, and results were expressed according to the CIELab color system (L^* lightness, a^* redness to greenness, and b^* yellowness to blueness). Total color difference (ΔE) values were calculated for comparison of color parameters of WSF and BSF and their corresponding pastas.

Data analysis and multivariate optimization. The data obtained were fitted through nonlinear regression to a second-order polynomial equation using the statistical software package Statgraphics Centurion XVI (StatPoint Technologies, Inc.), which was also were used to plot surfaces and in the optimization procedure. Modelling of the texture and cooking properties using these types of empirical models provides a better understanding of the food matrix and can consequently lead to improvements.

The general form of a second order model with k factors that describes the behavior of the response (Y) is given by Eq (1):

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ij} X_i X_j + \varepsilon \qquad (1)$$

where $X_1, X_2, \ldots, X_k$ are the independent variables, β_0 is a constant, β_i are the linear coefficients, β_{ij} are the interaction coefficients (when $_i = _j$, β_{ij} are the quadratic coefficients) and ε is the random error (Ferreira and others 2007). The interaction coefficients values determine the importance of each ingredient to the evaluated property, and the analysis of variance (ANOVA) reveals their statistical significance. The adequacy of the model for each property was evaluated through the levels of R^2, and the "lack of fit" test and the residue distribution was evaluated by the Durbin-Watson statistic.In order to obtain a formulation for the best cooking and textural properties, an optimization method proposed by Derringer and Suich (1980) was applied. Each response (Y) was standardized and transformed into individual desirability functions (d), which have a value of 1 when the response is on target and 0 when the response is unacceptable (Larrosa and other 2013). The weighted geometric mean of d is referred to as the composite desirability D (Eq (2)) as proposed by Derringer (1994), and expressed as:

$$D = \left(\prod_{i}^{p} d_i^{w_i} \right)^{\frac{1}{\sum w_i}} \qquad (2)$$

In Eq. (2), d_i is the individual desirability function of the i-th response ($i = 1, \ldots, p$), and w_i are weights that assign the importance of each response to the final product (Costa and others 2011). Next, an algorithm was applied to determine the levels of independent variables that maximize D (Ferreira and other 2007). Finally, the optimal formulation for each flour was prepared, and their properties were measured to test the models and to evaluate the estimations.

Sensory evaluation

In order to test pasta sensorial quality, the two optimum sorghum formulations, along with commercial rice flour pasta (Soyarroz, Argentina) and the control sample (Blu Patna, Uruguay) made from rice flour and egg were evaluated by a panel of 25 semi-trained judges. Previous the sensory evaluation of pasta samples a consensus about sensory quality attributes definition was reached; this implied precisely defining the descriptors and how to evaluate them to quantify attribute intensity, as well as agreeing upon the tasting procedure. Pasta firmness, chewiness and surface stickiness were marked using a discontinuous 7-point scale, and also asses surface appearance and an overall acceptability rating were assessed using a verbal 9-point hedonic scale as described by Bustos and other (2011). Data were statistically analyzed through an analysis of variance (ANOVA) using InfoStat software (Di Rienzo and other 2011).

Industrial production

With the aim of evaluating the ability of the formulation to be adopted on an industrial scale process, and to assess the effect of this process on the pasta attributes, the laboratory scale optimum sorghum pasta with the best results in the sensory evaluation was produced at an industrial site (Fraymar S.A., Jesus María, Argentina).

A batch of 70 kg of dry ingredients were weighed and placed in a feeding hopper with a continuous pneumatic transportation system that fed the mixer cavity of pasta extruder (Cerrini S.R.L., Italy). Then, water was added to produce the dough, after which it was formed into a short pasta (*pipe rigate*). Following extrusion, predrying of the pasta was carried out in a shaking chamber with a hot air counterflow. Finally, the pasta was dried on trays and shelves dryer with forced air circulation to a final humidity of above 10%. Industrially made pasta technological quality was evaluated through cooking properties (explained above).

Results and Discussion

Sorghum flour properties

The white sorghum flour (WSF) composition on a dry basis was: ash 1.2%, lipid 5.4%, protein 7.9%, and carbohydrates 85.5%; and for the brown sorghum flour (BSF) was: ash 1.3%, lipid 5.4%, protein 8.7%, and carbohydrates 84.6%.

Lipid values were higher than those reported by some other researchers (Florin 2011; Liu and others 2012), but similar to those given in a previous study (Palavecino and others 2016). However, the carbohydrates, protein and ash content observed were normal values for sorghum flour (Calderón-Sánchez and others 2011; Pellegrini and Agostoni 2015). Both samples pass through 20 mesh (0.83 mm), resulting in an average particle size of 0.27 mm complying with the regulations established by the *Codex Alimentarius*.

Several authors have reported a relation between pasting parameters and pasta quality. Here, on evaluating the pasting properties of both sorghum flours small but significant differences ($P < 0.05$) were only found for FV (WSF 3579 cP and BSF 3785 cP) and SB (WSF 2050 cP and BSF 2215 cP), with the other pasting parameters not showing significant differences between sorghum flours and presenting the following average values: PV 1993 cP, TV 1546 cP, BD 447 cP, peak time 5.7 min and PT 88.5 °C. The slight differences between both WSF and BSF pasting parameters were

Table 2–Minimum, maximum and average of 3 central points measured level for the selected variables.

	WSP			BSP		
Parameter	**Minimum**	**Central point**	**Maximum**	**Minimum**	**Central point**	**Maximum**
WA	131.13	166.17 ± 9.02	190.49	116.86	172.08 ± 4.27	194.15
SI	1.67	2.11 ± 0.07	3.10	1.77	2.35 ± 0.22	2.91
CL	4.00	4.75 ± 0.21	10.77	3.68	4.36 ± 0.17	11.94
Firmness	8.73	28.46 ± 1.42	45.17	8.73	17.55 ± 1.41	52.08
Chewiness	1.34	13.97 ± 2.26	24.54	0.96	8.74 ± 1.03	34.08

WSP, white sorghum pasta; BSP, brown sorghum pasta; WA, water absorption (%); SI, swelling index; CL, cooking loss (g/100 g); firmness (N) and chewiness (N)

Table 3–Regression coefficients and statistical significance for the prediction models.

	WSP					BSP				
Model coefficient	**WA**	**SI**	**CL**	**Firmness**	**Chewiness**	**WA**	**SI**	**CL**	**Firmness**	**Chewiness**
Constant	189.45*	3.62*	11.63*	−10.92*	−13.79	207.00*	2.97*	11.65*	−14.98*	−17.39*
X	−9.93	−0.72*	−1.39*	7.78*	7.29	2.37*	0.04*	−0.49*	7.28*	7.20*
A	2.92	−0.15*	−0.70*	2.54*	1.88*	−1.03*	−0.03*	−0.65*	1.47*	1.66*
E	−0.22	−0.07*	−0.29*	3.41*	2.42	−3.61	−0.04*	−0.10*	1.76*	2.17*
P	−1.99	−0.04*	−0.26*	1.66*	1.10	−1.13	−0.02	−0.44*	1.17	0.96
X^2	0.57	0.13*	0.12	0.39	−0.14	−4.53	−0.04	–	4.50*	1.38*
XA	−0.19	0.05*	0.03	−0.06	−0.05	−0.40	−0.01	−0.07*	−1.23*	−0.87*
XE	0.54	0.01	0.03	−0.82*	−0.44	1.34	–	−0.02	−0.20	0.24
XP	0.54	–	0.04*	−0.27*	−0.30	0.35*	0.01	0.05*	−0.47*	−0.34*
A^2	−0.49	–	0.03*	0.08	0.03	−0.43	−0.01*	0.03*	0.33*	0.19
AE	−0.13	–	0.02*	−0.08	−0.07	0.22*	0.01*	0.01*	−0.04	−0.14*
AP	0.10	–	−0.01*	−0.09*	−0.06	0.17	0.01*	0.01*	−0.07*	−0.04*
E^2	−0.31	–	–	0.03	−0.04	−0.24	–	−0.02	0.17*	0.01
EP	0.09	–	–	−0.08*	−0.04	0.07*	–	0.01	−0.10*	−0.09*
P^2	–	–	0.01*	−0.01*	–	−0.04	–	0.01*	0.01	–
R^2 (%)	53.15	79.86	77.61	73.99	78.45	75.48	78.57	84.09	91.36	82.18
Durbin-Watson (P)	0.292	0.125	0.552	0.360	0.990	0.276	0.734	0.842	0.571	0.842
Lack-of-fit (P)	0.190	0.099	0.251	0.062	0.437	0.073	0.647	0.203	0.052	0.294

*Significant at $P < 0.05$; -, < 0.00; WSP, white sorghum pasta; BSP, brown sorghum pasta; X, xanthan gum; A, egg albumen; E, egg powder; P, pregelatinized starch; WA, water absorption (%); SI, swelling index; CL, cooking loss (g/100 g); firmness (N) and chewiness (N).

in agreement to the flour´s compositions which was also very similar. These values were consistent with those reported in a previous study (Palavecino and others 2016) and to those reviewed by Zhu (2014). Gluten-free pasta should present a low pasting temperature to induce low CL. Also, flour should show a c-type pasting curve with a high and constant viscosity during pasta cooking, as high values of hot paste viscosity and final viscosity are usually associated with better noodle elasticity and improved textural properties (Thao and Noomhorm 2011; Heo and others 2014).

Cooking properties

Experimental data (Table 2) were fitted to the proposed model and its adequacy was evaluated (Table 3), with Figure 1 and 2 showing the response surfaces of the cooking and texture properties of pasta versus the ingredients with the highest influence.

The pasta cooking process involves a complex molecular transformation: starch swells because of contact with hot water, some granules gelatinize into the pasta structure but others are leached to the medium along with amylose chains, causing an undesirable sticky pasta surface and turbid cooking water (Beta and Corke 2001; Heo and others 2014; Larrosa and others 2016). The three-dimensional network that retains the granules in GF pasta is usually made up of proteins, pregelatinized starch and hydrocolloids (Marti and Pagani 2013).

The OCT was not chosen as a response of the experimental design; although, it was also evaluated. Its values ranged from 8 to 12 min for white sorghum pasta (WSP), and between 7 and 10 min for brown sorghum pasta (BSP), with the most frequent value being 9 min. It should be noted that all assays were performed at the OCT for each sample.

Good cooking quality is associated with high values of WA, which for WSP were between 131.14% and 190.49%, while for the BSP ranged between 116.86% and 194.15% (Table 2).These values are higher than those reported for other GF pasta formulations (Larrosa and others 2016; Loubes and others 2016), but similar to those given for wheat pasta (Bustos and others 2011) and wheat partially replaced with sorghum flour (Khan and others 2014). Regarding BSP, five effects were significant ($P < 0.05$) with the model explaining the 75.4% of the data variability. The Durbin-Watson statistic did not show autocorrelation in the residuals and the lack of fit statistic indicated than the model was adequate to describe the data. However, the WSP statistic parameters showed that the model poorly described the data. All samples in fact followed a similar tendency among the ingredients, with formulations containing a higher amount of egg (E) and especially that of egg albumen (A) having a lower WA, probably due to the formation of a more compact network that prevented water uptake of the other ingredients (Larrosa and others 2016).

As SI is driven by water intake and material release to the medium, then low values of SI is an important pasta quality factor (Heo and others 2014). In this study, SI decreased as ingredients (X, A, E and P) increased and therefore a desirable effect was produced (Table 3, Figure 1 and 2). Moreover, SI decreased sharply with increasing E and A (Figure 1a and 2a), due to the fast egg protein coagulation that limited starch swelling and leaching, whereas the formulations without A exhibited the maximum levels of SI.

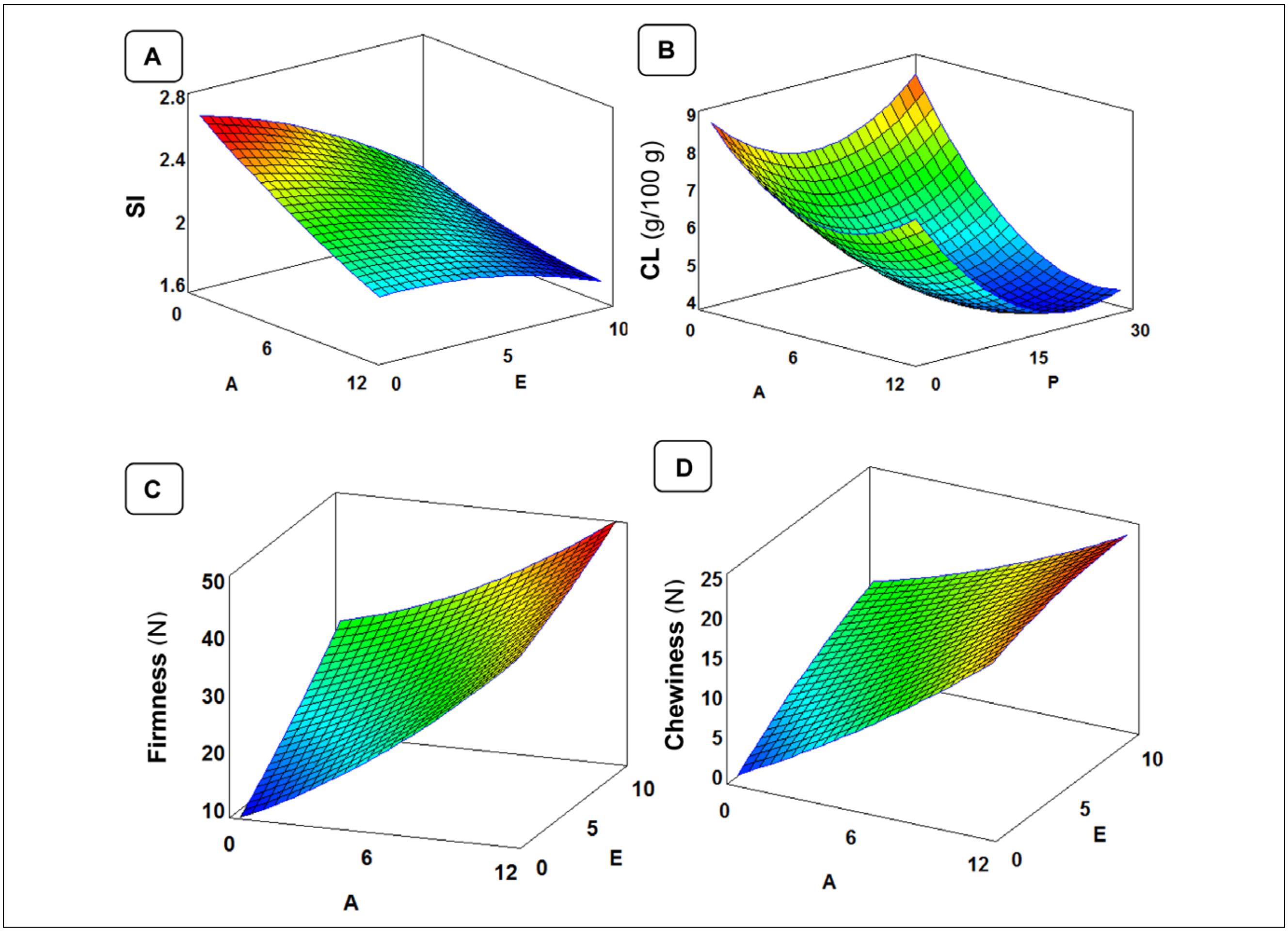

Figure 1–Relevant cooking (SI: swelling index, CL: cooking losses) and textural properties of WSP as a function of the ingredients (A: egg albumen, E: egg powder, P: pregelatinized starch) with the highest influence. Other two factors were kept constant in their average values.

Consumers acceptance depends on the pasta quality, which is strongly related to low values of CL and consequently to pasta resistance to disintegration and leaching (Heo and other 2014; Loubes and other 2016). The cooking loss values for WSP varied from 4.00% to 10.77%; and for BSP ranged between 3.68% and 11.94% (Table 2), with the lowest CL values in the present study being lower than those of the GF noodles and pasta reported by other authors (Suhendro and others 2000; Larrosa and others 2016; Loubes and others 2016; Wang and others 2016).

The statistic indicators showed that the model fitted the CL response for WSP and BSP, with the linear regression coefficients having significant negative effects (Table 3). Also, an increase in any ingredient produced a strengthening of the structure, thereby reducing the pasta CL in agreement with several other studies (Marti and Pagani 2013; Larrosa and others 2016; Loubes and others 2016; Wang and others 2016). The lowest CL values were found for the maximum levels of P, while the highest ones were associated to the samples without any A or P addition (Figure 1b and 2b). Finally, xanthan gum reduced the CL in pasta made from both sorghum flours and led to lower amounts of leached material during cooking, probably due to its capacity for gel formation aiding the starch retention mechanism.

Texture analysis

Pasta texture is a fundamental attribute with a main parameter being firmness, which is defined as the peak force during the first compression and has a close relationship to the network matrix strength, and therefore is a parameter to be maximized. Chewiness is the combination of three important texture parameters, and thus is a vital response to evaluate during pasta development. This is related to the elastic strength of the structure and usually decreases with the leaching of starch to the cooking water (Sozer 2009).

Table 3 shows the regression coefficients for firmness and chewiness and their statistical parameters, which indicated that the models fit well to the data. In contrast, the polynomial model did not adequately fit the adhesiveness results (data not shown). Although all the ingredients presented significant and positive effects on the firmness of WSP, A and E had the most relevant influence. Related to this, it can be observed (Figure 1c) that firmness increased with rising levels of A and E, indicating that egg proteins were responsible for the structure that provided the texture in WSP, as was also reported elsewhere (Sozer 2009; Larrosa and others 2016). In the case of BSP, however, X was the most relevant ingredient conferring firmness to BSP with only a minor contribution from A and E, and with no significant effect of P being found. Xanthan gum presented significant and positive linear and quadratic effects (Figure 2c), with this improvement in pasta firmness being due to its ability to be self-associated and to form a highly consistent gel in aqueous solutions (Sciarini and others 2010; Marti and Pagani 2013). Other authors (Larrosa and others 2013) have pointed out that nonstarch polysaccharides, in particular xanthan gum, are commonly used to mimic the gluten elastic

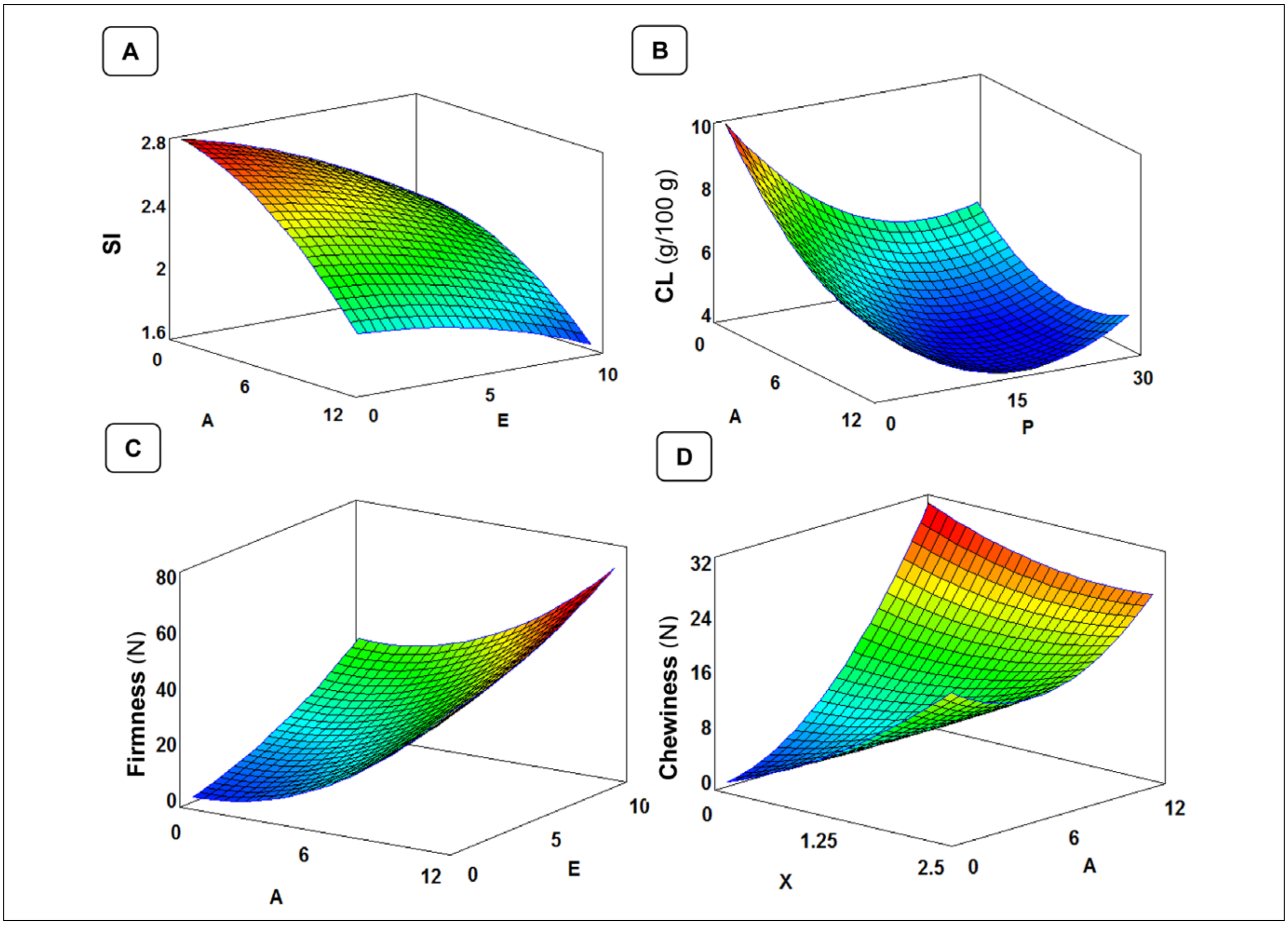

Figure 2–Relevant cooking (SI: swelling index, CL: cooking losses) and textural properties of BSP as a function of the ingredients (X: xanthan gum, A: egg albumen, E: egg powder, P: pregelatinized starch) with the highest influence. Other two factors were kept constant in their average values.

texture of pasta, improve firmness and impart mouthfeel to the end product.

The dissimilar behavior of both white and brown sorghum flours may be related to differences in the RVA parameters, as the mayor gelification and retrogradation capacities (higher FV and SB) of BSF produced greater pasta firmness (Table 2) (Thao and Noomhorm 2011; Liu and others 2012). However, it seems that egg proteins were less effective improving firmness in such a system.

The results of WSP chewiness showed that only A has a significant effect, and that the model successfully fitted the experimental data ($R^2 = 78.45\%$) (Table 3). In the response plot (Figure 1d) the surface generated by the interaction of A and E can be observed, with A having the most relevant effect. Of the ingredients, xanthan gum, egg powder, and pregelatinized starch had slight positive effects on this parameter.

The polynomial model adjusted 82.18% of the BSP chewiness variability, and the lack of fit and Durbin–Watson tests confirmed that this model was adequate to describe the functional relationship between the experimental factor and the response variable (Table 3). Several significant effects were found in BSP, but again, the most relevant was A. In addition, in the surface plot (Figure 2d), it can be seen that the response increased with rising amounts of A. At low content of A, the continuous increment of X increased the chewiness, however, a slight decrease in this parameter at high levels of both additives. It is known the improving effect of egg albumen on firmness and chewiness pasta due to the formation of a thin layer around starch granules (Marti and others 2014). It is suggested that, at high levels of A and X, egg protein layer was slightly weakened by xanthan gum. As in both sorghum pasta samples, the maximum chewiness values were observed in samples without P but with the maximum level of A, which confirms the low influence of pregelatinized starch and the positive effect of egg proteins.

Color

Color is a principal sensory attribute evaluated in pasta as it is the one the consumer first evaluates related to the product (Bustos and others 2015). In the present study, white and brown flour samples had significant ($P < 0.05$) differences in their color parameters. WSF presented higher L^* values than BSF (82.21 compared to 76.95) and chromaticity revealed that BSF was redder and less yellow than WSF with a^* values of 1.58 and 5.20, and b^* values of 14.28 and 10.95, respectively). These differences between flours were also reflected in pasta color. WSP had L^* values ranging from 58.51 to 65.57, while for BSP these values were between 47.27 and 57.17, indicating a higher luminosity in white sorghum pasta. In all cases, L^* increased with P and A due to white colored ingredients (data not shown). The increase of A and P significant decreased ΔE ($P < 0.05$), being those samples more similar to corresponding flour. At high A and P levels the ΔE values were 17.66 and 22.08 for WSP and BSP, respectively, while at low levels

Table 4–Ingredients level for optimum pasta formulation produced from white and brown sorghum flour.

	Optimum (g/100 g)	
Ingredient	**WSP**	**BSP**
Xanthan gum	0.0	2.5
Egg albumen	11.0	11.0
Egg powder	8.6	5.7
Pregelatinized starch	17.7	1.0

WSP, white sorghum pasta; BSP, brown sorghum pasta

of those ingredients the values were 21.90 for WSP and 27.08 for BSP. Regarding the a* parameter, although flour redness was relevant to pasta color, but the ingredients were not. In addition, the BSP a* values were higher (between 7.48 and 10.87) than WSP (between 2.93 and 5.24) and both presented higher values than other GF pasta (Thao and Noomhorm 2011; Giuberti and others 2015; Larrosa and others 2016) or regular wheat pasta (Bustos, Perez, and León 2011; Khan and others 2013) which ranged from –1.20 to 0.72.

The WSP was yellower than BSP and, in both cases, b* increased with E and *P* as was expected because of egg color, with average values being 17.33 for WSP and 12.38 for BSP. However, E did not significantly affect the ΔE values ($P > 0.05$). Similar results were also found for wheat pasta replaced with up to 40% of red and white sorghum flour (Khan and others 2013).

Despite the sorghum pasta color being different to that of other pasta, it must be noted that color variety usually implies the presence of healthy compounds (Krishnan and Prabhasankar 2012).

Multivariable optimization

In addition to explaining the behavior of variables using contour curves, the models fitted in this study can also be applied for optimization using the desirability function (D), which was used here to maximize WA, firmness and chewiness and to minimize SI and CL simultaneously. The results for this optimization suggested different combinations of ingredients that would optimize white and brown sorghum pasta quality (Table 4). For each model that adequately described response behavior (R^2, lack of fit and Durbin–Watson) the responses weights were assigned (Table 5), based on their relative importance as quality attributes from our experience in product development as suggested by Derringer (1994). Finally, pasta was made using these optimized levels, after which their attributes were evaluated.

Table 4 shows the optimum level of ingredients for pasta produced from WSF and RSF obtained through weighed multivariable optimization. These optimal formulations displayed differences, which was expected due to the disparity of results that the pastas had shown in the experimental design analysis. It is noteworthy that both formulations contained the maximum value of A, which is the ingredient that had the most relevant influence on the pasta attributes. Xanthan gum was not present in the WSP optimum formulation, but was required at its maximum amount for BSP. The amount of egg was higher in the WSP optimum mixture than in BSP, but in both formulations higher than average amounts of the experimental region was used, which again highlights the fact that egg was another ingredient with a significant influence on pasta quality. Regarding pregelatinized starch, the BSP optimum contained an amount close to the minimum, whereas WSP needed a quantity above the average. Thus, it can be inferred that, while the WSP formulation used the presence of starch to reinforce the pasta structure, the BSP made much more use of the X presence.

Table 5 shows the predicted values of the quality parameters by the corresponding model, along with and the results obtained from the experimental evaluation of the optimal formulations. The OCT for both formulations was 13 min, but WA was only used for optimization in BSP because the model fit was adequate in this case. In fact, the predicted WA for the BSP optimum was close to the minimum, whereas the experimental value was close to average of the experimental design, with the experimental WA for WSP optimum being lower than the minimum point of the design. These low WA values determined for optimum formulations were a result of due to the low weight chosen for this factor. Nevertheless, these values were satisfactory as explained above.

The experimental value of SI for WSP was similar value to the predicted one and to the minimum of the experimental design (Table 2). On the other hand, the experimental SI for the BSP optimum was higher than the predicted value, but was close to the minimum of the experimental design. In both cases, differences between the optimum SI and the maximum values obtained for SI in the experimental design were very large.

Although the CL values of the experimental design were completely acceptable for both sorghums, this factor's importance in GF pasta led to it to being given a high weight. The CL values obtained for the optimum formulations were slightly higher than the predicted values, but were close to the minimum and were low compared to the CL of conventional and GF pasta, as discussed above.

The optimized texture parameters, firmness and chewiness, were maximized. In WSP, the firmness experimental value was similar to predicted ones and to the maximum of experimental design. In contrast, the chewiness experimental values were higher than the model prediction or the maximum of the experimental design, whereas the BSP optimal firmness experimental value was lower than the predicted ones, but higher than all experimental design values. On the other hand, the experimental and predicted chewiness values from the optimal BSP formulation were similar but slightly lower than the design data.

Table 5–Optimization criteria for the selected variables and its predicted and experimental responses of pasta quality parameters for optimal formulations.

			WSP		BSP	
Parameter	**Objective**	**Weight**	**Predicted**	**Experimental**	**Predicted**	**Experimental**
WA	Maximize	1	–	120.75	117.02	147.61
SI	Minimize	2	1.64	1.62	1.67	1.92
CL	Minimize	4	4.16	5.76	4.05	5.38
Firmness (N)	Maximize	2	45.17	46.42	60.85	55.30
Chewiness (N)	Maximize	3	21.97	30.20	32.72	32.25

WA, water absorption (%); SI, swelling index; CL, cooking loss (g/100 g); WSP, white sorghum pasta; BSP, brown sorghum pasta

Table 6–Sensory evaluation and overall acceptability of optimum white and brown sorghum pasta (WSP and BSP, respectively) and commercial rice pasta.

Samples	Firmness*	Chewiness*	Adhesiveness*	Surface appearance**	Overall preference**
Optimum BSP	2.8a	3.1a	1.8a	4.4a	3.8a
Optimum WSP	3.7ab	3.3a	2.0a	5.4b	4.5b
Commercial rice pasta	4.4b	4.4b	3.0b	6.8c	5.8c

Within the same column, values with the same letter are not significantly different ($p > 0.05$).
Scale used:
*discontinuous 7 points scale
**verbal nine-point hedonic scale.

Sensory evaluation

Table 6 shows the mean values for each attribute of the two sorghum pasta samples and commercial rice pasta. Although no differences were found between the sorghum pastas regarding firmness or chewiness, commercial rice pasta revealed higher values than either sorghum or control pasta. Both white and brown sorghum pasta showed less adhesiveness than commercial rice pasta, with the control sample displaying the greatest value, which was related to the high CL level (8.39 g/100g).

Regarding surface aspect and overall preference, rice pasta had higher values than both sorghum pasta samples. In particular, WSP revealed higher values than BSP, which may have been a consequence of the marked color difference between the two flours. Thus, is summary, the WSP optimum presented better pasta sensorial attributes than the BSP optimum.

Industrial production

As a consequence of previous sensory results, the WSP optimum was selected to carry out the industrial test. It is noteworthy than the tested formulation did not have any problems during the pneumatic transport, hydration, mixing or extruding processes, which are normally used for wheat pasta production.

A textural parameter comparison between industrial and laboratory scale pasta was not possible due to the different shape of the industrial pasta (short pasta *pipe rigate*). However, cooking behavior was evaluated in industrial samples, with similar results obtained for SI and CL (1.55 and 5.18 g/100 g, respectively) and with a better performance in WA (208.43%) than that achieved for laboratory-made pasta. These results are in agreement with those of Alamprese and others (2007) where industrial GF pasta based on buckwheat and rice flours showed a greater weight increase but similar matter loss than laboratory-made ones.

In comparison with the commercial samples used for sensory evaluation, industrial WSP presented similar SI to that of rice pasta (1.57) but lower compared to control pasta (2.13). For the industrially produced sample, CL was higher than in commercial rice pasta (3.19 g/100 g), but lower that of commercial rice with egg pasta (8.39 g/100 g) with WA being higher than both commercials types (112.28% for rice pasta and 150.44% for rice with egg pasta).

Thus, the industrial process was able to improve WSP cooking behavior, probably due to a modification of the product structural characteristics, as observed by Alamprese and others (2007). In our case, the higher extrusion pressure developed by the industrial equipment may have permitted a better quality product to be obtained.

Conclusions

The results indicate that xanthan gum, egg albumen, egg powder, and pregelatinized starch had different effects on the quality parameters of gluten free pasta. Egg albumen proteins affected pasta attributes the most, with the combination of egg albumen and pregelatinized starch reducing material losses during cooking and that of egg albumen and powder egg increasing firmness and chewiness of the pasta. In addition, xanthan gum showed good results and minimized the swelling index of brown sorghum pasta and significantly helped to increase the chewiness. While albumin and pregelatinized starch modified the pasta color, resulting in pastas with high luminosity. The regression models adequately described the effects of the ingredients on the pasta quality attributes and enabled formulation optimization. As the experimental values of the optimal formulations were fully consistent with those predicted by both models, the validation was therefore very satisfactory. The sensory evaluation showed that the white sorghum pasta was more acceptable than the brown one, so the white optimal formulation was produced on a bigger scale. The industrial test revealed that dry GF sorghum pasta can be produced industrially, and this type presented better cooking properties than either the laboratory-made one or commercially available products derived from rice. Also, the formulation can utilize conventional wheat pasta facilities to produce GF sorghum pasta on an industrial scale. Summing up, this study affirmed that pasta from white sorghum flour constitutes a good alternative for gluten-sensitive individuals and is thus valuable for pasta producers.

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Author Contributions

PM Palavecino drafted the manuscript, supervise all the involved activities, and discuss the results. MB Heinzmann Alabí and MS Nicolazzi carried out most of the assays guided by our pasta expert MC Bustos who also helps with results interpretation. PD Ribotta and MC Penci made the experimental design and propose the present research.

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