INTERNATIONAL JOURNAL OF
FOOD
SCIENCES
and
NUTRITION

http://informahealthcare.com/ijf
ISSN: 0963-7486 (print), 1465-3478 (electronic)

Int J Food Sci Nutr, Early Online: 1–8
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DOI: 10.3109/09637486.2013.836737

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RESEARCH ARTICLE

Effects of extrusion conditions on physical and nutritional properties of extruded whole grain red sorghum (*sorghum* spp)

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Abstract

In order to analyze the effects of extrusion temperature (T: 164, 182, 200 °C) and grits moisture content (g/100 g sample) (%M: 14, 16.5, 19) on textural and physicochemical properties of red sorghum extrudates, whole grain flour was extruded according to a factorial experimental design. The higher values for specific mechanical energy consumption (1006.98 J/g) and expansion (3.36) were obtained at 164 °C–14%M and for sensorial hardness at 164 °C–19%M. While for specific volume, the highest value (10.41 cm^3/g) was obtained at 200 °C–14%M. Water solubility and water absorption were directly related with T and inversely with M. Microscopic observation of the samples indicates that the greatest cooking degree was obtained at 200 °C–4%M and the lowest at 164 °C–19%M. Extrusion at 182 °C–14%M allows obtaining an expanded product with good properties. Proximal composition did not show statistically significant differences with raw sample. Extruded sample showed a 25.4% reduction of available lysine and a 31% increase in protein digestibility.

Keywords

Extrusion, physicochemical properties, red sorghum, whole grain

History

Received 13 March 2013
Revised 24 June 2013
Accepted 18 August 2013
Published online 20 September 2013

Introduction

Cereals and cereal products are the basis of food pyramid and a daily intake of 6–11 servings are recommended. Despite recommendations of consuming at least three servings of whole grains (WG) each day (Dietary Guidelines of the United States, 2005), regular consumption of WG in western countries is approximately one serving/day (25 g). Food habits of populations are reflected in their pathologies: high cholesterol, overweight and high rates of cardiovascular disease, giving rise to the general need to reduce energy intake, cholesterol and saturated and trans fats, consistent with the increased consumption of fiber (Gargallo Fernández et al., 2012). This situation makes WG suitable to the dietary recommendations of the World Strategy suggested for the populations (CODEX, 2006).

Whole grain refers to intact cereal grain, ground, cracked or flaked, which main components (the starchy endosperm, germ and bran) are present in the same proportions as those in the intact grain (AACC, 2000a).

The incorporation of WG into the population diet is reduced by the lack of habits, coupled with the disadvantages of longer cooking time, and limited variety of products made of them, as a result of the difficulty of incorporating WG into food, since some of their components adversely affect the functional characteristics and the taste and texture of various formulations. One possibility is to process the grains by extrusion, an appropriate technology for cereals processing, which allows obtaining a variety of products with different textures and shapes (Drago et al., 2010).

Sorghum is drought-tolerant and resistant to water-logging, and grows in various soil conditions (Machado Alcolea et al., 2005). These characteristics make sorghum the staple crop of most food-insecure people from Africa, about 300 million people (Godwin & Gray, 2000). Nevertheless, the nutritional value of sorghum is impaired by endogenous anti-nutrients (phytates, tannins, phenolics, etc.) which can reduce the digestibility of nutrients, mainly proteins, and the absorption of minerals (FAO, 1995). One main nutritional advantage is that sorghum can be used for the development of gluten free foods intended for integrate the diet of the growing celiac population (Liu et al., 2012).

Food extrusion is a process in which a material is forced to flow under different conditions, heat and shear, through a given die, to form or expand the ingredient mixture. It can be considered as a continuous reactor in which a HTST (high temperature-short time) process is developed and transforms a variety of ingredients to intermediate products or finished ones such as: breakfast cereals, snacks (salty and sweet snacks), baby food, instant soups, breadcrumbs and coverage, textured vegetable protein, meat substitute, modified starches, confectionery, pasta (noodles), powdered drinks, biscuits, health food, granola, cones, etc. (González et al., 2002).

Sorghum grain has a chemical composition similar to that of corn and the processing technology for the production of food and industrial products from corn or other cereal are applicable to sorghum. This could efficiently exploit its potential as food in the production of various products and the application of the extrusion process is much recommended for doing that (Martínez & Pau, 1992).

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When extrusion cooking process is applied to WG, the presence of germ and hull particles reduces the degree of cooking reached by the extrudates, thus the specific volume and sensorial properties, in comparison with extrudates obtained from degermed and dehulled grains, thus the optimum extrusion conditions needed for an acceptable expanded product are different (González et al., 2002). The aim of this work was to study the effects of extrusion conditions on physical and nutritional properties of whole grain red sorghum (*sorghum* spp) extrudates.

Material and methods

Raw material

Commercial red sorghum grains (*sorghum* spp) were ground in a Buhler MIAG roll mill (BUA AG, Uzwil, Switzerland) according to a milling diagram which allows obtaining whole grain grits with a particle size adequate for extrusion. Particle size was between 1920 and 420 μm, with less than 1% sample fine fraction (below 420 μm).

Methods

Experimental design

To analyze the effects of extrusion variables on textural and physicochemical properties of whole grain sorghum extrudates, a 3^2 factorial design was used. Factors levels were selected according to preliminary trials, values being: 164, 182 and 200 °C, for extrusion temperatures and 14.0, 16.5 and 19.0 g water/100 g sample, for grits moisture. Eleven extruded samples were obtained and response surface methodology was utilized to analyze the effects of extrusion factors on selected responses.

Extrusion process

Extrusion experiments were carried out using a 20 DN Brabender single screw extruder (Duisbug, Germany) at the following conditions: 4/1 screw compression ratio, 3×20 (diameter–length) mm die and 150 rpm screw speed. Experimental samples were taken after stationary state was established, then torque (BU) and mass output (g/min) were measured.

Physical properties

Specific mechanical energy consumption (SMEC) was calculated according González et al. (2002): with the following formula:

$$\mathrm{SMEC} = KTN/Q_S$$

where, K is a constant ($61.3 \times 10^{-3}\,\mathrm{J\,g^{-1}}$); T: torque in Brabender Units (BU); N: screw rpm and Q_S: mass output at feeding moisture content.

Expansion (E) was calculated as the ratio of extruded product diameter and die diameter, taking the average of 10 measurements on 10 different places along the sample.

Specific volume (SV) expressed as the product volume per gram was calculated using the mass output coming from the extruder (g · min and d.b.) and the product volume, which is calculated from the length of product per minute and the product diameter.

An amount of 100 g representative of each sample were first ground with a Retsch hammer mill with a 2 mm sieve and then with a Ciclotec mill through a 1 mm sieve and used for measurement of water absorption, water solubility, retrogradation consistency (R), and microscopic observation.

Water absorption, as spontaneous uptake of water, was determined using Baumman method according to González et al. (2002). About 50 mg of sample was spread on the filter paper, and the volume of absorbed water was measured after the equilibrium was reached.

Water solubility was calculated as soluble solids by 100 g flour (d.b.). This was done by dispersing 2.5 g of flour in 50 mL water at 25 °C, agitating during 30 min and centrifuging at $2000 \times g$; soluble solids were obtained after evaporation in an oven at 105 °C.

Retrogradation consistency (R), expressed as Brabender units (BU), was measured with a Brabender Amylograph (Duisburg, Germany) at 50 °C at the end of the cooling step of the amylogram. The amylogram was done using a flour dispersion of 10 g solids/100 g and a head of 250 cm gf.

For microscopic observation, a Leitz (Germany) microscope with polarized light was used to observe the presence of native starch granules, those showing the Maltese cross (MC). Due to the difficulty to quantify this fraction, samples were classified in four groups:

X: sample with more than 75% of granules with MC
XX: sample containing granules between 75% and 50% with MC
XXX: sample containing granules between 50% and 25% with MC
XXXX: sample containing less than 25% of granules with MC.

Extrudate hardness evaluation

Extrudate hardness was evaluated by two assays: sensory hardness (SH) and mechanical resistance (MR). Part of extruded samples were air-dried in an oven at 50 °C until 6% moisture content was reached, this moisture level being considered adequate for texture evaluation. Each dried sample was divided in several portions and kept in plastic bags hermetically sealed until its evaluation. Product texture was evaluated by a trained panel (three judges), according to Fritz et al. (2006), using a hardness nine-point scale, the highest score (9) corresponding to the hardest sample. The score given to each sample was obtained by consensus among the judges.

MR evaluation was carried out using an Instrom Universal Testing Machine (Model 2519.105). A 50-mm length sample piece was compressed at a compression speed of 10 mm/min, using an 8-mm diameter probe and a 5000 N load cell, at a speed of 1 cm/s.

Structural changes: crystallinity

Starch structure was evaluated using Diffraction X-ray techniques. Diffractograms were obtained with a Shimadzu DX.1 diffractometer, measuring the area of the three characteristic peaks corresponding to the native starch structure (at 2θ: 13, 18 and 23 degrees). Crystallinity (%C) was expressed as the ratio of the sum of the areas corresponding to those peaks and the total area of the diffractogram (Merayo et al., 2011).

Assessment of phytic acid content

AOAC (1995) method was used to measure phytic acid (PA) content. It is based on the extraction of phytic acid in acid solution, followed by separation through an anionic resin and colorimetric assessment of phosphorus content using phosphomolybdic acid reagent (AOAC, 1993). Results were expressed as percentage of loss of phytic acid:

$$\%\mathrm{PAL} = (\mathrm{PA}_{\text{raw sample}} - \mathrm{PA}_{\text{extruded sample}}) \times 100/\mathrm{PA}_{\text{raw sample}}.$$

Determination of total extractable phenolic compounds

An acetone: water (80:20) extraction system was used to extract phenolic compounds. The samples were dispersed at 10 g/100 mL, stirred during 30 min and then centrifuged at $8000 \times g$. Total extractable phenolic content (TEPC) from supernatant was

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quantified using Folin–Ciocalteu reagent (Singleton et al., 1999). A standard curve with serial gallic acid solutions (0–100 mg/L) was used for calibration. Results were expressed as mg gallic acid/-g of dry sample.

Antioxidant properties. Trolox equivalent antioxidant capacity (TEAC)

To estimate the antioxidant activity (AA), ABTS$^{\bullet}+$ radical cation decolorization assay according to Pukalskas et al. (2002) was used. To estimate the TEAC, a concentration-response curve for the absorbance at 734 nm for ABTS$^{\bullet}+$ as a function of concentration of standard Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid) solution (0–2.5 mmol/L) in 0.01 mmol/L (PBS, pH 7.4) was performed. The absorbance reading was taken at 6 min after initial mixing and the results were expressed as μmol TEAC/g sample.

Proximate composition assess

Proximate composition (moisture, fats, proteins, ash and dietary fiber was determined according American Association of Cereal Chemists methods (AACC, 2000b)).

Available lysine content and protein digestibility

The method of Carpenter modified by Booth (1971) was used for measuring available Lysine, and the *in vitro* method according to Rudloff & Lönnerdal (1992) was used to assess protein digestibility.

Mineral bio-accessibility

The method of dialyzability developed by Miller et al. (1981) modified by Drago et al. (2005) was used to estimate iron and zinc bio-accessibility (DFe% and DZn%, respectively). This method measures mineral dialyzability under controlled pH conditions after a digestion-simulating physiological process.

Statistical analysis

All determinations were done in duplicate and averages were used to analyze the effect of variables on different responses using response surface methodology. Surface response methodology was used to obtain surface regression models for each response as a function of extrusion temperature and flour moisture content. Statgraphics plus 5.1 was used for the statistical analysis.

Results and discussion

Figure 1(a) shows red sorghum extruded samples obtained according to the experimental design. Table 1 shows values of SH, MR, solubility (S), water absorption (WA), retrogradation consistency (R), microscopic observation, crystallinity (%C) and total extractable phenol content (TEPC) corresponding to experimental extruded samples.

ANOVA results (Table 2) showed the degree of significance (*p* values) corresponding to the effects of each polynomial term of the regression model. As the lack of fit was not significant in all cases, the regression models obtained can be considered adequate to describe the effects of T and M on each response.

Effects of extrusion conditions on SMEC and physical properties

For SMEC, only T term was significant ($p < 0.05$), although the terms M and TxM were not negligible (*p* values: 0.0712 and 0.0979, respectively) and can explain the slight curvature and distortion of the plane observed in Figure 1(b). SMEC was inversely related to T and M, which is in agreement with the fact that friction level inside the extruder decreases as T

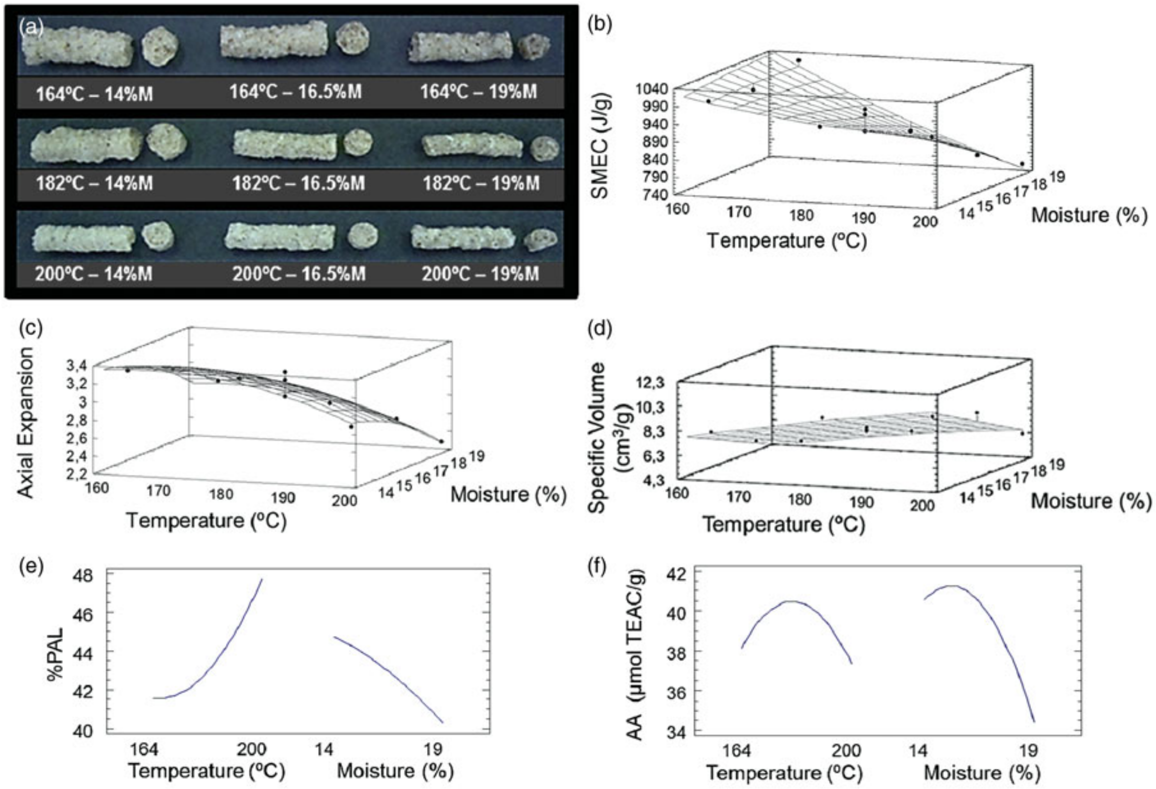

Figure 1. Red sorghum extruded samples obtained according to experimental design (a), Surface response obtained for specific mechanical energy consumption (SMEC) (b), expansion (c), specific volume (d). Principle effects for percentage of phytic acid loss (%PAL) (e) and antioxidant activity (AA) (f) as a function of temperature and moisture.

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and M increase. Similar tendency was obtained by González et al. (2002), for extrusion of maize grits. The slight effects of M observed at 160 °C could be attributed to the presence of germ which would attenuate the reduction of friction caused by an increase of M.

Table 2 shows that only the linear terms T and M, were significant ($p < 0.05$) for expansion (E) and similarly as SMEC, E was inversely related to T and M (Figure 1c). The highest value corresponded to the sample obtained at 164 °C and 14 g water/100 g sample, suggesting that melt elasticity level was also inversely related to T and M. This indicates that, as T increased much thinner porous wall in the extrudate would be obtained and consequently a reduction in expansion was observed (Figure 1a). On the other hand, as M increases porous size would be reduced and their walls would be thicker, thus a reduction of E occurred. Similar tendency was found for maize grits and maize-soy mixture by González et al. (2002) and Pérez-Navarrete et al. (2006).

In the case of specific volume (SV) only the linear terms (T and M) were significant ($p < 0.05$) (Table 2). Surface response (Figure 1d) shows that T and M affected SV in an opposite way: SV increased with T and decreased with M. The observed tendency was similar to that observed for maize grits (degermed and dehulled maize) (González et al., 2002). Taking into account that SV can be considered as a cooking degree (CD) indicator (González et al., 2002), it is clear that both, SMEC and E are directly related with SV when the comparisson is done at the same T, but an opposite relation is observed with T at the same M, which is in agreement with the response surfaces.

Table 1. Effects of extrusion variables (T and M) on: sensory hardness (SH), mechanical resistance (MR), solubility (S), water absorption (WA), retrogradation consistency (R), microscopic observation, crystallinity (%C) and total extractable phenol content (TEPC) corresponding to whole red sorghum extruded samples.

T (°C)	M (%)	SH	MR (kgf)	S (g%)	WA	R (BU)	Microsc Obs.	%C	TEPC (mg AG/g)
164	14.0	6	33.20	53.74	5.20	115	XX	27.36	1.20
	16.5	8	35.43	50.61	4.73	200	X	25.39	1.24
	19.0	9	40.64	42.71	4.35	340	X	29.16	1.32
182	14.0	4	28.90	54.59	4.97	110	XXX	34.27	1.37
	16.5	6	34.48	53.18	4.94	240	XXX	27.74	1.29
	16.5	5	33.24	51.28	5.07	225	XXX	29.39	1.26
	16.5	5	32.63	51.32	5.03	250	XXX	31.05	1.21
	19.0	7	38.84	46.85	4.59	210	XXX	26.73	1.29
200	14.0	1	26.59	54.68	5.28	210	XXXX	30.01	1.14
	16.5	3	32.33	53.34	5.10	285	XXXX	31.23	1.28
	19.0	5	33.45	52.57	4.98	300	XXX	25.26	1.40

Effects of extrusion conditions on sensorial hardness and mechanical resistance

Regarding sensory hardness (SH), ANOVA results show that only the linear terms (T and M) were significant and that T and M affected SH in an opposite manner, increasing with M and decreasing with T, suggesting that SH would be inversely related with CD, as it was observed by Pérez et al. (2008).

The highest SH value corresponded to sample obtained at 164 °C and 19 g water/100 g sample, which would correspond to the lowest CD, while the softer sample was that obtained at 200 °C and 14%M, which would be the one with the highest CD. An inverse relation was obtained between SH and SV: $SH = -1.1425\ SV + 14.045$ ($R^2 = 0.80$).

MR followed the same tendency as SH did (Figure 2a) and a good direct correlation was obtained: $MR = 1.5796\ SH + 25.139$ ($R^2 = 0.81$). Only the linear terms (T and M) were significant. These results are in agreement with those obtained by Drago et al. (2011), working with extruded maize: soy (88:12) mixture.

Effects of extrusion conditions on amylographyc retrogradation consistency, hydration properties and microscopic observation

Table 1 shows the effects of extrusion variables (T and M) on hydration properties (Solubility, S and water absorption, WA), retrogradation consistency (R), microscopic observation and crystallinity (%C), corresponding to the experimental samples.

Table 2 shows degree of significance (p values) corresponding to the effects of each polynomial term of the regression model. As the lack of fit was not significant in all cases, the regression models obtained can be considered adequate, to describe the effect of T and M on each response.

It is observed for S, that only the linear terms were significant, although the term TxM is no negligible ($p > 0.0542$), which explain the distortion of the planar surface obtained (Figure 2b). S was inversely related with M, this effect being more noticeable at low T. Also, S increased as T increased, particularly at high moisture level. Similar tendency was observed by Martínez & Pau (1992), working with integral sorghum flour and for three different moisture content: 12, 15 and 18 g water/100 g sample. This would indicate that at low moisture level, mechanical effects (friction level) are more important, however at high M, thermal effects predominate. These results are in agreement whit those obtained by González et al. (2002), working with corn grits.

In the case of WA, ANOVA results (Table 2) were similar to those corresponding to S. When cooking process is completely attained (no native granules are present in the extrudate), WA should increase with M and decreased with T (González et al., 2002). In our case, the tendency observed for the effect of T and

Table 2. Degree of significance (p values) of the polynomial regression model coefficients, corresponding to specific mechanical energy consumption (SMEC), axial expansion (E), specific volume (SV), sensory hardness (SH), mechanical resistance (MR), solubility (S), water absorption (WA), retrogradation consistency (R), microscopic observation and crystallinity (%C), phytic acid loss (%PAL), total extraible phenol content (TPC) and antioxidant activity (AA) corresponding to whole red sorghum extruded samples.

	p Value											
Source of variation	SMEC	E	SV	SH	MR	S	AA	R	%C	%PAL	TEPC	AA
T	0.0263	0.0511	0.0035	0.0101	0.0181	0.0363	0.0210	0.0452	0.1680	0.0025	0.4188	0.4021
M	0.0712	0.0352	0.0013	0.0194	0.0090	0.0157	0.0109	0.0055	0.0398	0.0048	0.1056	0.0150
TxT	0.5720	0.2543	0.2639	0.8979	0.9914	0.8648	0.4047	0.0298	0.1073	0.0193	0.4942	0.0441
TxM	0.0979	0.8706	0.1844	0.4778	0.7879	0.0542	0.0526	0.0330	0.0654	0.0800	0.5352	0.5690
MxM	0.8782	0.3545	0.8301	0.8979	0.9793	0.2397	0.1546	0.0411	0.3670	0.1985	0.1218	0.0372
Lack of fit	0.6643	0.9056	0.0808	0.8414	0.2628	0.5940	0.1892	0.0747	0.0751	0.2636	0.4188	0.6246

$p < 0.05$ means significant differences.

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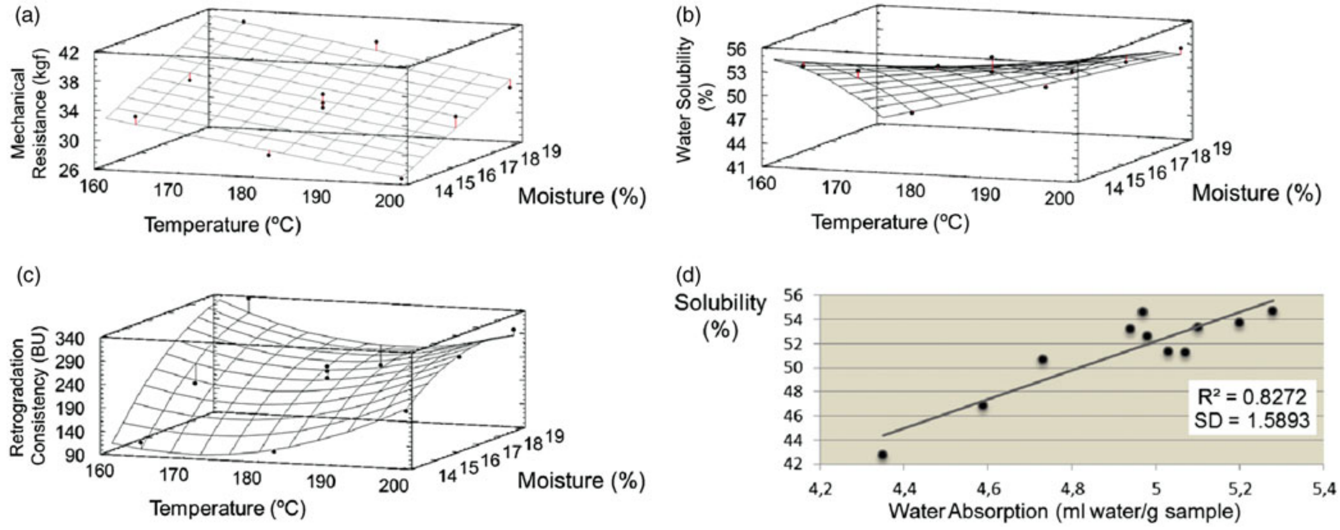

Figure 2. Surface response obtained for mechanical resistance (MR) (a), water solubility (%) (b), retrogradation consistency (BU) as a function of temperature and moisture (c) and relationship between water absorption and solubility (d).

M on WA (Table 1), would indicate an incomplete destruction of native granular structure as it was reported by Haller (2008).

Moreover, it is known that for low levels of CD, WA is inversely related wit S, but beyond certain CD level, WA decreases as S increases (González et al., 2002). The direct relation between WA and S, observed in Figure 2(d), together with the results obtained corresponding to microscopic observation (Table 2), confirm the above statement.

Regarding retrogradation consistency (R), not only the effects of the linear terms were significant ($p < 0.05$), but also T × T, M × M and M × T (Table 2), which explain the type of surface obtained (Figure 2c). It is observed that R increased with M and T (at low M level). At high M level, this trend is changed and a minimum at around 182 °C is observed. The increase of R as M increases is in agreement with González et al. (2002) who have reported that R is inversely related to CD.

Water solubility, which is directly related to cooking degree, and the retrogradation consistency are taken as cooking degree indicators. Both properties are inversely related as it was discussed by González et al. (2002).

In order to discuss the effect of T and M on hydration properties (solubility and water absorption), amylografic retrogradation consistency and microscope observation, it has to be taken into account that extrusion cooking is a thermo-mechanical process, thus shear and temperature effects are the main factors affecting CD. It is well known that gelatinization temperature (or fusion temperature) is inversely related with starch moisture content (Blanshard, 1987). However, even though extrusion temperature is higher than GT, it is possible to find native granules in extruded samples because residence time distribution verified with single screw extruder is wide enough to permit some granules going out the extruder at a time insufficient to accomplish the cooking process. This means that extrusion cooking process converts starch granules in different ‘‘structural states’’ (native, gelatinized, fragment of granules and macromolecular aggregates), which have to be taken into account when the effects of factors such temperature (T) and moisture (M) are being analyzed. These two factors act in opposite direction on friction exerted inside the extruder, and consequently the effect of T and M on CD will depend on the relative magnitude of the effect of each factor. For extrusion conditions corresponding to low CD, native and gelatinized granules predominates, then for a decrease of M or an increase of T, an increase of gelatinize and fragmented granules will occur as a consequence of a reduction of the amount of native granules. On the other hand, for conditions corresponding to high CD, fragment of granules and macromolecules dispersion will predominate (Haller, 2008).

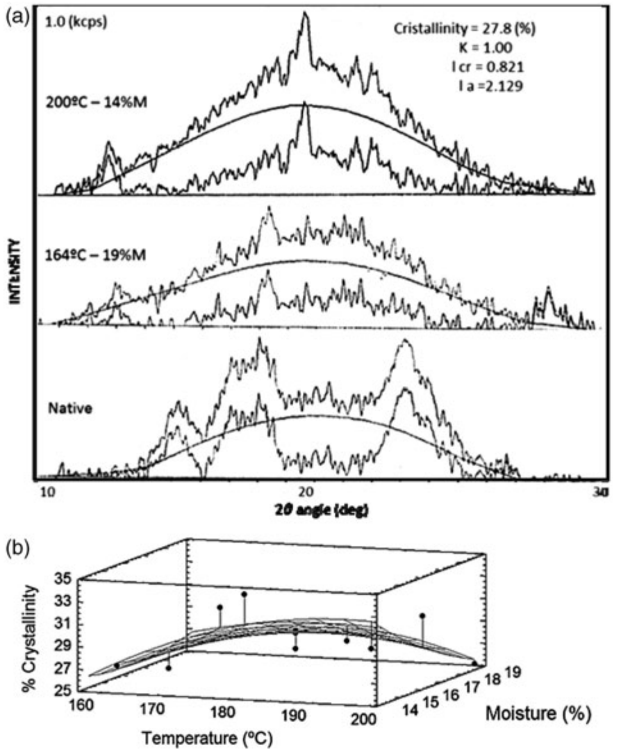

Figure 3. Diffractograms corresponding to the extreme conditions of extrusion (200 °C – 14%M and 164 °C – 19%M) and native sorghum flours (a) and surface response obtained according to experimental design for %crystallinity as a function of temperature and moisture (b).

In this way, an extruded sample visually homogeneous could be not from the point of view of CD, which is defined as the degree of destruction of the starch granular structure (González et al., 2002).

Effects of extrusion conditions on crystallinity

Figure 3(a) shows the X-ray diffraction (XRD) pattern obtained for native and two extruded samples. Native sample showed a type

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A pattern, characteristic of the starch from cereals (Zobel, 1988), with a degree of crystallinity of 45.2 ± 3.1%.

After extrusion, the diffraction pattern changed due to the disorder and losing of crystalline structures, and the formation of amorphous state (65.73–74.74%) as a consequence of cooking (Quevedo et al., 2007). Table 2 shows the ANOVA results for %C. The most significant terms were M and TxM (0.0654).

Figure 3(b) shows the surface response for the effects of M and T on %C. It is observed that %C decreased when M increased, the lower %C value corresponding to the sample obtained at 200 °C–19% M.

All precooked flours showed an amorphous pattern greater than that obtained for native flour as consequence of the reduction of crystallinity, indicating degradation of the starch granules during extrusion.

Effects of extrusion on cooking degree

It has been demonstrated that specific volume and water solubility are good indicators of CD and that they are directly related (González et al., 2002; Pérez et al., 2008). The extrusion process disrupted the crystalline structure of starch from whole grain sorghum flour, as observed by XRD. On this regard, our results showed that MR of extrudate structure is inversely related to CD and that the hardest sample was that obtained at 164 °C and 19% M, which presented the lowest CD (lowest values of SV and S). On the other hand, the softer sample with the highest CD was obtained at 200 °C and 14%M.

Effect of extrusion on phytic acid, phenolic compounds and antioxidant activity

The content of PA-phosphorus corresponding to raw whole sorghum was 0.52 g/100 g sample, which corresponds to 1.83 g PA/100 g sample. It was observed for %PAL, that linear and T × T terms were significant (Table 2). Figure 1(e) shows that %PAL increased as T increased and H decreased. PA content ranged from 1.10 to 0.91 g/100 g, corresponding to %PAL values of 39.8 and 50.2% (Table 1), these values being obtained for the lowest and highest CD, respectively. Losses of PA (23%) were also observed for whole rye extruded at 170 °C (Fretzdorff & Weipert, 1986) and extruded bean flour (50–100%) (Antón, 2009).

Regarding TEPC, the value obtained for raw whole sorghum was 2 mg GA/g sample. After extrusion, TEPC was reduced in the range of 30% to 41%, the reduction being lower at 14%M and higher at 19%M, regardless of T value. Nevertheless, none of the terms of the polynomial was significant (Table 2), the surface response for TEPC had the same tendency than that of AA surface (Figure 1f). The reduction in TEPC could be due to destroying the phenolic structure or decreasing extraction related with phenolic interactions with other matrix components, such as proteins (Emmambux & Taylor, 2003).

Regarding AA, raw sorghum presented a value of 41.51 μmol TEAC/g sample. Similarly, Ragaee et al. (2006) observed a value of 51.7 ± 0.57 μmol TEAC/g for *Sorghum bicolor* L.

Concerning the effect of extrusion variables on AA, M linear and T × T and M × M terms were significant (Table 2). Figure 1(f) shows that AA decreased as M increased. The percentage of AA reduction ranged 1.1–24.8%. Similarly, Awika et al. (2003a) observed a reduction of 0–30% in antioxidant capacity. This effect could be related with TEPC reduction after extrusion.

Proximal composition of raw and extruded (182 °C–14%M) whole grain sorghum flours

Taking into account the physical and sensory characteristics of the extruded samples, the extrudate obtained at 182 °C and 14%M was selected for further analysis since it showed good properties for an expanded product. This sample was evaluated regarding nutritional composition and compared with raw flour (Table 3). No statistically significant differences between both samples were observed. The same results were observed by Martínez & Pau (1992), who developed instant products using white sorghum, both whole and dehulled, and extruding at three different moisture contents (12, 15 and 18%) and 110 °C temperature.

Table 3. Proximal composition and nutritional parameters of raw and extruded (182 °C–14%M) whole red sorghum flours.

	Raw sorghum (g/100 g)	Extruded sorghum (g/100 g)
Protein[a]	11.01 ± 0.09	10.67 ± 0.04
Fat[a]	2.72 ± 0.05	2.72 ± 0.02
Dietary fiber[a]	8.79 ± 1.30	9.92 ± 1.15
Ash[a]	1.53 ± 0.01	1.53 ± 0.03
Available Lys (g Lysine/100 g protein)	4.33 ± 0.38	3.23 ± 0.76
Protein digestibility (%)	53.18 ± 1.95	70.02 ± 0.15
Fe bio-accessibility (%)	11.15 ± 2.00	9.94 ± 1.18
Zn bio-accessibility (%)	21.31 ± 3.50	9.94 ± 1.00

Values are expressed as mean ± standard deviation.
[a]DB, dry base.

Available lysine and protein digestibility of raw and extruded (182 °C–14%M) whole grain sorghum flours

Table 3 shows the values of available lysine content in raw and 182 °C–14%M extruded sample. A reduction of 25.3% for available lysine was observed for the extruded product. This value is within the range reported for other extruded materials. Björck et al. (1984) studied the effect of extrusion cooking on the nutritional value of wheat flour and whole wheat flour proteins. Values between 63 and 100% for Lys retention were observed, while the losses of other amino acids were small. Konstance et al. (1998) studied available lysine of extruded corn and soybean blends. The Lys losses ranged from 3 to 20.5% for less critical to more severe conditions. An excessive Maillard reaction can result in Lys losses up to about 50%, as was observed by De La Gueriviere et al. (1985) in the extrusion of wheat. In the case of rice flour, extrusion performed at 15% of M and 120–150 °C reduced the total lysine content to 11–13% (Eggum et al., 1986). Moreover, Pérez-Navarrete et al. (2006) evaluated the effects of extrusion on the nutritional quality of corn and beans blend and found that Lys availability decreased between 15 and 25%.

Thus, Lysine availability can be used as a measure of processing damage (Walker, 1983), since at the conditions normally used for extrusion, Maillard reactions are promoted and a negative effect on the availability and digestibility of amino acids could be observed (Asp & Björck, 1989). Extrusion increased protein digestibility (Table 3). The values obtained were similar to those observed by Maclean et al. (1983) for *in vivo* protein digestibility (46% and 81% for whole and dehulled-extruded sorghum, respectively).

The extrusion process increased the protein digestibility by 31%. This confirms that the increase in protein digestibility is one of the advantages attributed to the extrusion cooking process (Drago et al., 2007b). Increasing protein digestibility can also result from the reduction of polyphenols, since the low-protein digestibility is due to protein–protein, protein–carbohydrate, protein– (poly) phenol and carbohydrate– (poly) phenol interactions (Taylor & Taylor, 2002).

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Mineral bio-accessibility

Table 3 shows that DFe% was not affected by extrusion (*p*: 0.617), but DZn% was significantly reduced (*p*: 0.005). Likewise, Drago et al. (2007a) observed that DFe% from *Phaseolus vulgaris* flour did not change after extrusion at 180 °C y 17%M, but DZn% decreased. It is known that PA is a potent inhibitor of Fe and Zn availability (Alonso et al., 2001), thus the reduction in PA caused by extrusion was not enough to improve mineral bio-accessibility.

Conclusions

In the case of sorghum and for a single screw extruder, such as Brabender 20DN, more severe conditions have to be applied in order to obtain extrudates having a cooking degree enough for a good expanded product. The analysis of the physicochemical, sensory characteristics and hydration properties of the extruded samples, allow selecting the extrudate obtained at 182 °C and 14 g water/100 g sample, since it showed good properties for an expanded product. No statistically significant differences in proximal composition were observed between raw and sample extruded at 182 °C–14%M. The extruded sample chosen showed a reduction of available lysine of 25.4% and in counterpart found and increase protein digestibility of 31% compared to the raw sample. Although Fe bio-accessibility was not affected by extrusion, Zn bio-accessibility decreased. Extrusion also affected total phenolic content and antioxidant activity. This study is a first approach to study and explain the effects of extrusion conditions on physiochemical characteristics of expanded products made of whole sorghum.

Declaration of interest

This study was financed by project PICT 1105 from ANPCyT. The authors declare no conflicts of interest. The author alone are responsible for the content and writing of this article.

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