



Comparison of properties of native and extruded amaranth (*Amaranthus cruentus* L. – BRS Alegria) flour

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ABSTRACT

The aim of this study was to compare some of the properties of native and extruded amaranth flour obtained under mild and severe extrusion conditions. The chemical composition of the flours was similar. Flours obtained by both extrusion processes presented high solubility in water, low values of L* (luminosity) and an absence of endothermic peak on the DSC method. Water absorption, retrogradation tendency, final viscosity and the viscous behavior by rheology analysis were also studied. The results indicate that extruded flours have a good potential as an ingredient for food exposed to heat treatment at a high temperature and mechanical shear, for use in instant meal products. On the other hand, original flour properties are comparable to those of amaranth starch, which exhibits similarly high quality paste stability, low solubility in water, and elastic behavior, and could be used as a substitute for raw flour in a range of food formulas.

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1. Introduction

Amaranth has recently become a focus of interest for its high nutritive values and great potential as a functional food given its cholesterol-lowering effect observed in animal models (Mendonça, Saldiva, Cruz, & Arêas, 2009; Plate & Arêas, 2002).

Despite its nutritional and health importance, amaranth flour has not gained sufficient research attention to its physicochemical properties. Nevertheless, some hydration and thermal properties of individual amaranth components (protein, fiber, starch) have been widely discussed in the literature (Kong, Bao, & Corke, 2009; Martínez & Añón, 1996; Repo-Carrasco-Valencia, Peña, Kallio, & Salminen, 2009). Studies investigating the properties of amaranth flour are scarce, e.g. examining it as a complex system. It is known that the extrapolation of data on individual components to infer the behavior of more complex systems such as flours can be misleading because interactions among components could be overlooked (Sandoval, Nuñez, Muller, Della Vale, & Lourdin, 2009).

While the native flour presents a particular behavior, cooked flour could be more advantageous for application in food products due to its instantaneous characteristics. In order to obtain cooked flour, thermoplastic extrusion can be used. This is a versatile and very efficient technology, widely used in grain processing and has

become a well established industrial technology, with a number of food and feed applications (Cheftel, 1986). A wide range of thermo-mechanical and thermo-chemical processes are involved, including shear, Maillard reactions, starch gelatinization, protein denaturation and hydrolysis. These processes result in the physical, chemical and nutritional modification of food constituents (Arêas, 1992). Moreover, the extrusion of amaranth resulted in a ready-to-eat snack with a better nutritional value compared to traditional snacks made from maize (Chávez-Jáuregui, Pinto e Silva, & Arêas, 2000; Chávez-Jáuregui, Pinto e Silva, & Arêas, 2003).

Only a few studies have reported the extrusion cooking of pure amaranth or of amaranth blended with other grains. Despite this lack of data, extruded amaranth flour may possibly serve as a useful alternative in highly nutritious food products and could also improve the physicochemical, functional and sensory characteristics of products. In addition, the functional properties of native and extruded amaranth flour have not been reported. Against this background, the present investigation was undertaken to examine hydration and thermal properties of native and extruded amaranth flour in order to identify their potential application as food ingredients.

2. Materials and methods

2.1. Defatted and non-defatted amaranth flour

Amaranth (*Amaranthus cruentus* L) of the BRS Alegria variety, provided by EMBRAPA – Brazil, was used for this study. The flour

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was prepared by grinding seeds on a Buhler MU-202 laboratory mill (Bühler Ltd, Uzwil Switzerland). One part of this flour was defatted with five parts of n-hexane (m:v) for 24 h (residual lipid was less than 1 g/100 g). Both flours were packed in polyethylene bags and stored at room temperature before further use. These flours were labeled whole native flour (WNF) and defatted native flour (DNF).

2.2. Extrusion process

Extrusion experiments were carried out in a laboratory single screw extruder, L/D ratio 15.5:1. (RXPQ Labor 24, Inbramaq Ind. Maq. Ltd., Ribeirão Preto, Brazil). The barrel had three zones with independent electric element heaters and a 3.55:1 compression ratio screw. The following conditions were set based on preliminary experiments: 3.6 mm die diameter, feed rate at 150 g/min (dry matter) and temperature calibrated in first and second zones, 30 °C and 80 °C, respectively. Feeding was provided by a vibrating duct and the amount of the material dropped in the screw hopper could thus be controlled. The choke feed rate for the lower screw speed was then determined (150 g/min of dry matter) and adopted for the higher speeds. Two experimental points of a fractionated factorial design were chosen in order to compare extreme conditions of extrusion (mild and severe extrusion). All variables and their levels were pre-determined in previous assays employing an incomplete design with four independent variables. The independent variables were type of flour, moisture, barrel temperature of third zone and screw speed. Based on this previous assay we selected feed moisture and temperature as independent variables and we kept constant all others. All extrusion conditions were repeated twice and the results presented are the mean of these replicates. Based on these previous results, two extrusion conditions were then defined, a 'mild' and a 'severe' one. The mild extrusion utilized a defatted flour with 15 g/100 g moisture, at 120 °C and 158 rpm, whereas the severe extrusion (SE) utilized a whole flour with 25 g/100 g moisture, at 180 °C and 237 rpm. These flours were labeled mild extrusion flour (MEF) severe extrusion flour (SEF).

The flours were conditioned to obtain the desired moisture for extrusion by adding the required amount of water to the flour in a planetary mixer (Erweka, Mod. AR403, Basel, Switzerland). The hydrated flour was sealed in polyethylene bags and stored at 5–8 °C for 48 h prior to extrusion.

The temperatures of all the sections were set, and, upon reaching temperature, corn grits were extruded at a screw speed of 263 rpm (maximum rotation) to stabilize the flow at ~200 g/min before processing the amaranth flour. Finally, the mixture was fed to the extruder and after 5 min and stable ampere input readings, the samples were collected. All processing conditions were controlled and recorded using a software program for Windows developed in the laboratory of Food Functional Properties (Faculty of Public Health, University of São Paulo, São Paulo, Brazil).

After extrusion the samples were collected, cooled to room temperature under natural convection conditions. The samples were then milled to a 0.149 mm granule size. They were labeled as extruded amaranth flours and kept at 10 °C until analysis. Untreated flours were stored in the same manner as the extruded samples.

In order to assess possible effects of flour particle size on the analysis, granule sizes were checked using a Malvern Mastersizer S-MAN 5005 (Malvern Instruments Ltda, Malvern, UK). (data not shown).

2.3. Chemical composition

The chemical composition of the flours including the moisture, fat, protein and ash content, were determined by the method

described in AOAC (1997). The dietary fiber was analyzed using the enzymatic and gravimetric method according to Prosky, Asp, Schwiser, Devries, and Furnas (1988); starch was determined according to the method of Rickard and Behn (1987).

2.4. Amylose determination

Starch was quantified by enzymatic hydrolysis as described by Rickard and Behn (1987). Amylose content was determined following the method ISO 6647 (International Organization for Standardization, 1987). Amylopectin content was equal to the value obtained by subtraction of amylose from total starch.

2.5. Color

The color of the samples was determined in triplicate using the equipment ColorQuest XE (Hunter Lab, ColorQuest, USA). The CIE $L^*a^*b^*$ system was employed. This system determines the L^* , a^* and b^* values, where L^* represents lightness with 0 for black and 100 for white; a^* represents the opposition between green and red colors ranging from positive (green) to negative (red) values; and b^* is the yellow/blue opposition also ranging from positive (yellow) to negative (blues) values. In the CIE $L^*a^*b^*$ color space a^* and b^* values exhibit minima and maxima values that depend on L^* value.

2.6. Water absorption and water solubility indexes

To determine the water absorption (WAI) and the water solubility indexes (WSI), the methodology proposed by Anderson, Conway, and Griffin (1969) was followed.

2.7. Pasting properties

Pasting properties of amaranth flours were determined using a Rapid Visco Analyzer (RVA-4, Newport Scientific, Warriewood, Australia) according to Ragae and Abdel-Aal (2006). The pasting temperature (PT), peak viscosity (PV, the maximum hot paste viscosity), holding strength or trough viscosity (the trough at the minimum hot paste viscosity), final viscosity (FV, the viscosity at the end of test after cooling to 50 °C and holding at this temperature), breakdown (BD, peak viscosity – holding strength or trough viscosity) and setback (SB, final viscosity – holding strength) were determined with ThermoLine for Windows software (Version 2.0). The viscosities are presented in Rapid Visco Units (RVU).

2.8. Thermal properties

Thermal properties were analyzed using a Differential Scanning Calorimeter (DSC822, Mettler Toledo, Schwerzenbach, Switzerland) according to González, Carrara, Tosi, Añón, and Pilosof (2007) with some modifications. Amaranth flour (13.0 ± 0.02 mg, wb) was weighed into an aluminum pan and 47.0 ± 0.02 μ L of distilled water was added. The pan was hermetically sealed and equilibrated at room temperature for 24h, then heated at the rate of 10 °C/min from 15 to 110 °C with an empty sealed pan as a reference. Parameters including onset (T_0), peak (T_p), conclusion (T_c) and enthalpy (δH) were determined.

2.9. Dynamic viscoelastic parameters

Temperature at which storage modulus increased, storage modulus at the end of heating (G'_h) and storage modulus at the end of cooling (G'_c) were measured with a Paar Physica Controlled Stress Rheometer (MCR 300, Gaz, Austria), equipped with parallel plate geometry. Measurements were made in the linear viscoelastic

region determined in tests of constant frequency and variable amplitude. Strain and frequency were set at 0.01% and 1 Hz, respectively. The temperature of the bottom plate was controlled with a Peltier system (Viscotherm VT2, Paar Physica, Gaz, Austria), and liquid paraffin was applied to the sample's exposed surface to prevent water evaporation. Native and extruded amaranth flour aqueous suspension (0.20 g wt) were heated from 20 °C to 90 °C at a rate of 10 °C/min, kept at 90 °C for 10 min (sufficient time to allow the storage modulus equilibrium), then cooled to 20 °C at 10 °C/min and held for 10 min at this temperature.

2.10. Statistical analysis

All analyses were carried out in at least duplicate and data expressed as mean \pm standard deviation employing the Statistica version 7.1 software (Statsoft Inc., Tulsa, OK, USA).

3. Results and discussion

3.1. Proximate composition

The proximate composition, on a dry basis, of the native and extruded amaranth flours are depicted in Table 1. The results obtained for native flours are in agreement with those reported by previous studies on the same amaranth variety: protein at around 15 g/100 g (the nitrogen factor used was 5.85 according to Berghofer & Schoenlechner, 2002), and lipid of around 7 g/100 g (Capriles, Coelho, Matias, & Arêas, 2006). Starch, fiber and ash amounts were also in accordance with Capriles et al. (2006) and Mendonça et al. (2009). The extruded flour compositions were similar to those of native flour. Thus, both mild and severe extrusion process did not significantly affect the composition of the flours. Although vitamin and mineral amounts were not determined in the present study, according to Cheftel (1986), the thermoplastic extrusion process did not reduce these nutrients.

3.2. Color

Hunter color values (L^* , a^* , b^*) of flours are shown in Table 2. Many reactions take place during extrusion cooking that may affect color. The color observed in extruded products might be due to caramelization or the Maillard reaction (Cheftel, 1986). Lysine and other amino acids present in the raw material probably react with the reducing sugars, favored by the processing conditions, which lead to darkening of the extruded products (Gutkoski & El-Dash, 1999).

Luminosity (L^* value) was decreased by the extrusion process whereas a^* and b^* values were increased, findings which are consistent with those of Ilo, Liu, and Berghofer (1999). L^* values of

Table 1
Composition (dry basis) of native, defatted and extruded defatted amaranth flours.

Nutrients (g/100 g) ^a	Whole native flour	Defatted native flour	Mild extrusion flour	Severe extrusion flour
Protein ^b	12.8 \pm 0.1	13.3 \pm 1.3	13.0 \pm 0.2	12.8 \pm 0.1
Lipid	6.0 \pm 0.1	1.0 \pm 0.0	0.5 \pm 0.0	3.2 \pm 0.1
Total starch	69.1 \pm 0.1	69.6 \pm 0.4	69.2 \pm 0.1	69.1 \pm 0.0
Amylose	0.3 \pm 0.1	0.5 \pm 0.0	0.7 \pm 0.0	0.6 \pm 0.0
Amylopectin	68.8	69.1	69.4	69.7
Total fiber	13.0	13.8	14.0	11.2
Soluble	1.9 \pm 0.7	2.1 \pm 0.7	3.2 \pm 0.4	2.9 \pm 1.0
Insoluble	11.0 \pm 1.0	11.7 \pm 1.1	10.9 \pm 1.4	8.2 \pm 1.1
Ash	2.9 \pm 0.1	3.0 \pm 0.1	2.9 \pm 0.1	3.0 \pm 0.1

^a Values expressed as mean \pm SD ($n = 3$).

^b Calculated using $N \times 5.85$ for all samples.

Table 2

L^* , a^* and b^* compounds of CIELAB color system for native, defatted and extruded defatted amaranth flours.

	L^*	a^*	b^*
Whole native flour	79.9 \pm 0.0 ^a	2.1 \pm 0.0	14.9 \pm 0.1
Defatted native flour	81.4 \pm 0.2	1.9 \pm 0.1	12.6 \pm 0.2
Mild extrusion flour	69.6 \pm 0.3	5.0 \pm 0.1	19.1 \pm 0.3
Severe extrusion flour	58.7 \pm 0.3	8.01 \pm 0.0	24.7 \pm 0.3

^a Values expressed as mean \pm SD ($n = 3$).

WNF and DNF (79.9 \pm 0.02 and 81.4 \pm 0.24, respectively) were higher than MEF and SEF (69.6 \pm 0.29 and 58.7 \pm 0.26, respectively) which indicated high luminosity of native flours compared to the extruded flours. All flours showed positive a^* values, which indicated a slight red tint in these samples. The b^* value, an indicator of (–) blue and yellow (+), indicated the presence of a mild yellow component in all flours, particularly in the extruded samples.

Manufacturing processes such as extrusion and baking can affect final product colors. Thus, to obtain and maintain the desired color, it is important to monitor and control ingredient color as well as to monitor the product throughout the manufacturing process.

3.3. Water solubility and water absorption index

Table 3 shows the results for the native and extruded amaranth flours. The results show that the extruded flours have a higher WSI than native flours. Such high WSI values for extruded samples have been previously reported by Gutkoski and El-Dash (1999) for cereals and by Dogan and Karwe (2003) for quinoa, a pseudocereal as is amaranth.

The WSI values of the extruded flours were similar to those found by González, Carrara et al. (2007) who used a similar methodology to evaluate a starch-rich fraction modified by extrusion. González, Torres, De Greef, Tosi, and Ré (2000) suggested that the amaranth endosperm structure is much weaker than those of other waxy cereals and proposed solubility as a direct indicator of degree of cooking in extruded cereals because solubility is related to the degree of rupture of the granular structure. Additionally, according to Colonna, Doublier, Melcion Monredon & Mercier (1984), the increase in solubility in the extruded products is attributed to dispersion of amylose and amylopectin molecules following gelatinization under mild processing conditions, and to formation of low molecular weight compounds under harsher conditions.

In contrast, as the gelatinization becomes more intense, an increase in starch fragmentation takes place which lowers absorption of water (Colonna et al., 1984).

Table 3

Hydration and pasting properties of native, defatted and extruded defatted amaranth flours.

	Whole native flour	Defatted native flour	Mild extrusion flour	Severe extrusion flour
WSI (g/100 g)	14.8 \pm 0.1 ^a	15.4 \pm 0.1	57.6 \pm 2.0	54.1 \pm 1.3
WAI (g gel/g of dry matter)	3.0 \pm 0.02	3.3 \pm 0.1	4.2 \pm 0.1	3.8 \pm 0.1
PV (RVU)	94.3 \pm 2.8	120.5 \pm 0.1	6.0 \pm 0.1	3.1 \pm 0.1
Breakdown (RVU)	34.4 \pm 0.6	36.0 \pm 0.4	2.5 \pm 0.1	3.1 \pm 1.5
Final viscosity (RVU)	70.6 \pm 3.3	95.0 \pm 0.4	4.7 \pm 0.2	0.9 \pm 1.7
Setback (RVU)	10.8 \pm 1.0	10.6 \pm 0.7	1.2 \pm 0.1	2.9 \pm 0.1
Paste temperature (°C)	76.6 \pm 0.00	75.7 \pm 0.1	–	–

RVU: Rapid Visco Units.

^a Values expressed as mean \pm SD ($n = 3$).

WAI of extruded flours were slightly higher than those of native flours where these results are in line with those reported by González, Carrarra et al. (2007).

WAI depends on the availability of hydrophilic groups and on the gel formation capacity of the macromolecules (Gomez & Aguilera, 1983). It is a measure of damaged starch together with protein denaturation and new macromolecular complex formations. Although swelling is evidently a property of amylopectin (Tester & Morrison, 1990) and amaranth has a high level of amylopectin, the low values obtained for this index can be attributed to almost total degradation undergone by starch granules in both mild and severe extrusion processes.

3.4. Pasting properties

Pasting properties of native and extruded amaranth flours are summarized in Table 3. The PT of native flour was around 76 °C and represent initial temperature of gelatinization when viscosity starts to increase.

Pasting properties of native flour were also similar to the results for amaranth starch reported by Kong et al. (2009), who studied fifteen cultivars of this grain. The starchy characteristic of amaranth flour may have contributed to some extent to the similar isolated starch results while the differences might be due to the presence of other constituents in the flour (Ragaee & Abdel-Aal, 2006). The PV of the amaranth native flours presented low values compared to amaranth starch, which may be ascribed to the low amylose content found for the samples analyzed in this study (less than 0.5 g/100g). In a study of fifteen cultivars of amaranth, Kong et al. (2009) found the smallest value of PV to correspond to the starches with the lowest amylose content. Indeed, according to some authors (Kong et al., 2009; Liu, Yu, Xie, & Chen, 2006) the amylose content directly affects viscosity, i.e. the higher the amylose content, the higher the viscosity is.

Peak Viscosity and PT were not very pronounced for extruded samples. This indicates molecular and structural degradation in the starch granules during extrusion cooking (Ilo et al., 1999). Indeed, this behavior has previously been demonstrated in several other studies (Gutkoski & El-Dash, 1999; Menegassi, Leonel, Mischan, & Pinho, 2007). Since PV was very low, the other viscosity parameters were also low, where this is a characteristic of extruded samples.

The point at which amylose leaching and alignment occurs is commonly associated with a breakdown in viscosity. The ability of starches to withstand heating at high temperature and shear stress is an important factor in many processes. High values of BD are associated with high peak viscosities, which in turn are related to the degree of swelling of the starch granules during heating. Higher amounts of starch granules with a high swelling capacity result in a higher peak viscosity. This is the case of the native flours

compared to the extruded flours which had very low peak viscosity and BD. The peak viscosity often correlates with quality of the end-product and also provides an indication of the viscous load likely to be encountered by a mixing cooker (Ragaee & Abdel-Aal, 2006).

During cooling, re-association between starch molecules, especially amylose, will result in the formation of a gel structure and viscosity will therefore increase to reach the final viscosity. This phase is commonly described as the setback region during which retrogradation and reordering of starch molecules take place. Low setback values were found for both native and extruded samples, indicating low rate of starch retrogradation and syneresis (Ragaee & Abdel-Aal, 2006).

3.5. Thermal parameters

DSC thermograms allowed analysis of transition temperatures (i.e. onset, T_o ; peak, T_p ; conclusion, T_c), as well as transition enthalpies. Because the various constituents of flour have different thermal transitions, interpretation of DSC parameters was done considering only starch and protein, which represent the major components of flour (about 70% and 15%, respectively).

DSC results are presented in Table 4 and Figs. 1 and 2. All the flour samples exhibited at least two endothermic peaks at different temperatures, with the exception of severe extrusion flour. They are referred to hereafter as transitions 1, 2 and 3 (T_{p1} , T_{p2} , T_{p3}). The first T_p for whole and defatted native amaranth flour were similar (76 °C) and coincided with the paste temperature obtained by RVA. Some authors (Baker & Rayas-Duarte, 1998) have reported that the gelatinization temperature of amaranth starch was higher than wheat or rice starches. They have suggested there are more organized regions in amaranth as higher temperatures were needed to record a melting transition. These T_p and their respective δH could indicate starch gelatinization whereas the other small peaks could be attributable to protein denaturation. In fact, Baker and Rayas-Duarte (1998) reported a T_p for amaranth starch of around 70 °C and Kong et al. (2009) observed T_p for fifteen cultivars of amaranth which ranged from 68 °C to 78 °C. Martínez and Añón (1996) reported different temperatures for amaranth protein denaturation. Albumin and glutelin presented T_p of 64 °C and 70 °C, respectively, which indicate lower thermal stability. It was also observed a higher T_p (in excess of 90 °C), corresponding to globulin, albumin-2 and glutelin subfraction that are more thermostable. However, it is worth noting that these comparisons to the present work are not straightforward because in this case all amaranth fractions must be considered and also distinct water:starch proportions were used.

Initially, it was thought that the small endothermic peak observed for whole native flour could be attributed to an amylose–lipid complex. However, this peak still occurred after defatting at the same temperature (defatted native flour), indicating that it

Table 4
Thermal transitions (DSC) and enthalpy for native, defatted and extruded defatted amaranth flours (dry matter).

Sample	Number of transition	Temperature (°C)			Total enthalpy δH
		T_o	T_p	T_c	
Whole native flour	1	70.5 ± 0.6 ^a	76.1 ± 0.5	82.8 ± 0.5	5.5 ± 0.3
	2	93.4 ± 0.7	99.8 ± 1.0	104.4 ± 1.5	
	3	108.1 ± 3.1	110.3 ± 2.9	113.7 ± 1.8	
Defatted native flour	1	69.4 ± 0.9	76.0 ± 0.3	83.1 ± 0.2	6.6 ± 0.2
	2	92.9 ± 2.5	100.1 ± 1.0	113.3 ± 6.7	
Mild extrusion flour	1	93.4 ± 2.1	97.2 ± 4.3	100.3 ± 3.2	1.2 ± 0.5
	2	103.7 ± 3.0	109.0 ± 0.3	113.0 ± 1.5	
Severe extrusion flour	2	103.2 ± 3.9	107.5 ± 0.2	111.2 ± 2.6	0.7 ± 0.3

^a Values expressed as mean ± SD ($n = 2$); T_o , T_p and T_c denote onset, peak melting and conclusion transition temperatures.

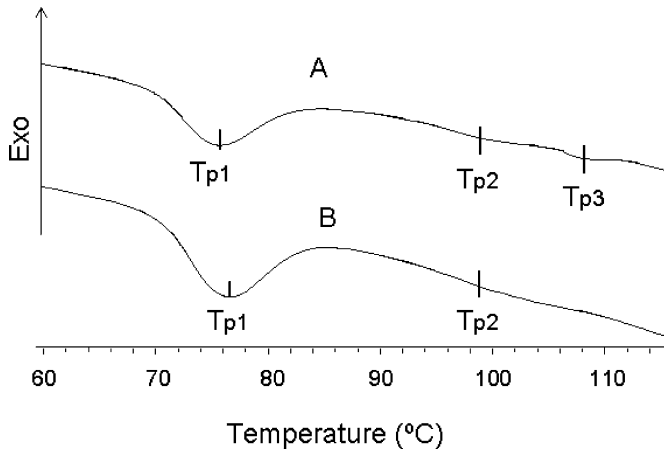


Fig. 1. DSC thermograms of whole (A) and defatted (B) amaranth flours.

was not related to the lipid content of the flour. In addition, lipid–amylose complexes start to melt only at temperatures approaching 110 °C (Doublie, Paton, & Llamas, 1987) and the waxy characteristic of amaranth flour starch did not confirm this hypothesis, again suggesting denaturation of thermostable protein, as outlined earlier. It is noteworthy that Okechukwu and Rao (1997) also reported two DSC peaks in a study with cowpea protein plus starch (cowpea and corn) gels, the first peak being due to starch gelatinization and second to protein denaturation.

The absence of an endothermic peak at around 70 °C for extruded flours could indicate total degradation of starch that occurred prior to the extrusion process. Indeed, these results agree with those discussed previously in that the extruded flours also showed a very small peak and low final viscosity compared to native flours.

González, Carrara et al. (2007) reported similar values of enthalpy for an extruded amaranth starch-rich fraction to those observed in this study. At the lowest moisture (12 g/100 g) and temperature (150 °C and 175 °C) levels, the δH reported by these authors were 0.90 J/g and 0.85 J/g, respectively. These authors attributed this enthalpy to gelatinization of starch and suggested that some starch granules retained their crystalline structure after extrusion under these particular extrusion conditions, since the other extrusion conditions did not present δH . Nevertheless, if this was this case, it is not possible to ascertain whether the δH is

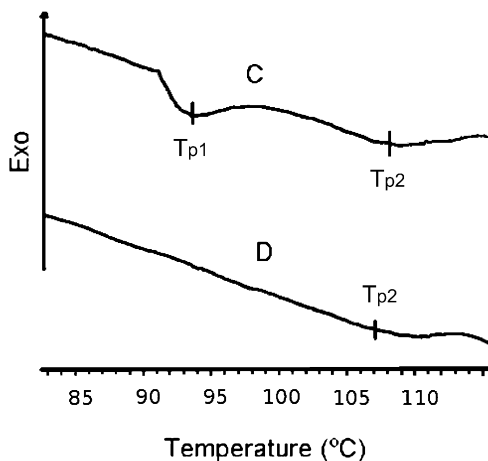


Fig. 2. DSC thermograms of defatted amaranth extruded at mild (C) and severe (D) conditions.

attributed to gelatinization starch or denaturation protein, because the starch was not pure (starch-rich fraction) and the temperature of this peak was not reported.

3.6. Dynamic viscoelastic parameters

Dynamic rheometry was employed to determine the temperature at which storage modulus increases ($T_{G'inc}$), and to ascertain storage modulus at the end of heating (G'_h) and storage modulus at the end of cooling (G'_c).

Since the macromolecular substances responsible for network formation in food systems are primarily polysaccharides and proteins (Tabilo-Munizaga & Barbosa-Cánovas, 2005), the results for dynamic viscoelastic properties were interpreted taking into account the starch and protein content (around 70% and 15%, respectively).

The storage and loss moduli analysis of native flours showed that the viscoelastic behavior of these flours was characteristic of a gel, considering that G' value was higher than G'' value (Fig. 3A and B). At lower temperatures storage modulus was lower than loss modulus, but at around 60 °C, G' starts to increase and exceed G'' . The temperature at which the storage modulus showed a sharp increase ($T_{G'inc}$) was considered as the temperature the structure formation started (González et al., 2007). In fact, the native flour $T_{G'inc}$ values were lower (approximately 10 °C) than the T_{onset} values obtained on DSC analysis at the same concentration (20 g/100g). In fact, there is no consensus on the data obtained from DSC and rheometry techniques (Sandoval et al., 2009). Nevertheless, some authors (Eliasson, 1986; González et al., 2007) hold that the initial increase of storage modulus is related to the hydration and swelling process of the amorphous regions of starch granules, which would be in turn related to the prior development of $T_{G'inc}$ compared to T_{onset} values. Some reports in the literature state that in the specific case of starchy food products, DSC has not shown sufficient sensitivity to detect the glass transition (Champion, Le Meste, & Simatos, 2000). Based on our results, it seems that the initial swelling process is also not detected by this technique.

From the above discussion, it can be concluded that in native flours $T_{G'inc}$ values represent starch gelatinization together with the gelation of protein that presents lower thermal stability (as outlined above).

The temperature range in which the storage moduli of native flour reached the maximum values during the heating period was 75–80 °C. This coincides with the peak temperatures obtained by DSC (75–76 °C) and also with the temperatures corresponding to the amylographic peaks (76–77 °C), reported by González et al. (2007).

During all heating period and when held at 90 °C, storage modulus did not decrease indicating resistance to rupture of the flour starch granules. On the other hand, during the cooling period, a sharp increase in the storage modulus was observed of almost double the values reached at the end of the heating period. This indicates that although the gel structure was formed mainly during the heating period, it was further strengthened upon cooling.

The $T_{G'inc}$ values were similar in both whole and defatted flours. Therefore, lipids were considered to have no influence in this parameter. Chiotelli and Le Meste (2003) reported that the addition of triglycerides in concentrated potato starch preparations had no effect on the gelatinization process or rheological behavior of starch during heating.

On the other hand, G'' was found to be higher than G' in extruded flours in the whole temperature range studied with no clear $T_{G'inc}$, thereby indicating a viscous behavior (Fig. 3C and D). This difference was maintained throughout the cooling period, in which a slight increase in both G' and G'' is observed during holding

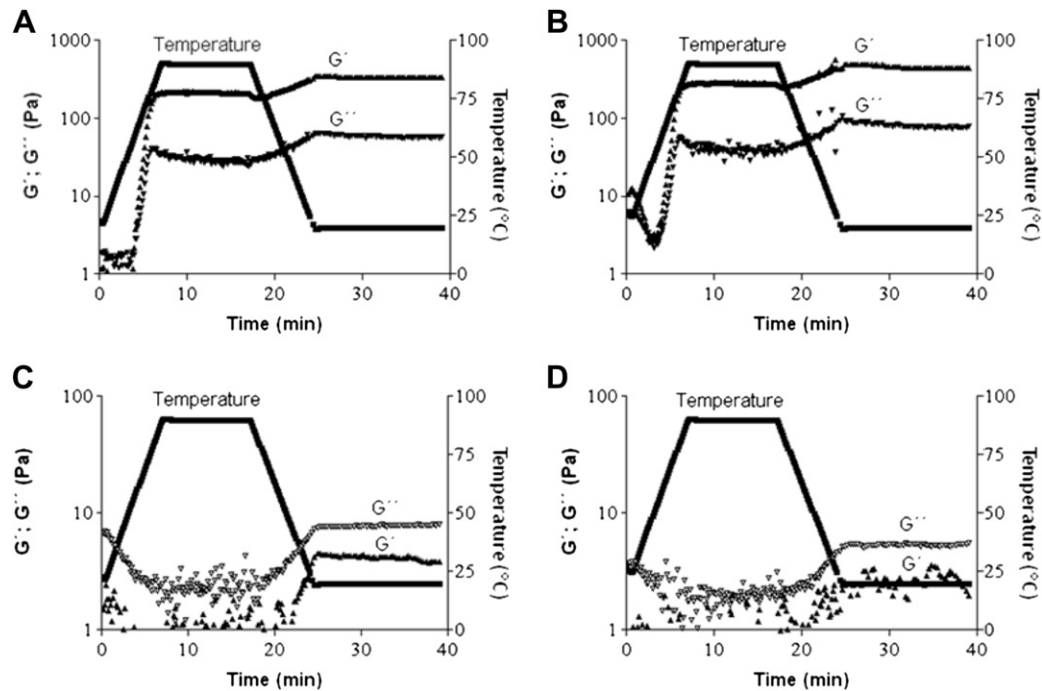


Fig. 3. Evolution of storage (G') and loss (G'') moduli of whole (A) and defatted (B) native flours, and after mild (C) and severe extrusion (D) of defatted amaranth.

at 20 °C. These results are consistent with the DSC data and indicate that there were physical and chemical changes as a consequence of the process conditions. Similar results were reported by González, Carrara et al. (2007) who reported a complete loss of the crystalline and granular structure of flours obtained from extrusion cooking. However, Cindio, Gabriele, Pollini, Peressini, and Sensidoni (2002) reported higher storage modulus than loss modulus in extruded cereal mixtures across the entire range of temperature, indicating an elastic behavior. Sandoval et al. (2009) reported the same behavior in a ready-to-eat cereal formulation obtained by other high temperature processes, and compression molding.

4. Conclusion

The results showed that the chemical composition of the two flours was similar. Flours obtained by both extrusion processes presented high solubility in water and low values of L^* (luminosity), absorption in water, final viscosity and retrogradation tendency. Three endothermic transitions were observed for whole native amaranth flour that did not change after defatting. Two of them were observed after extrusion in mild conditions and only one after extrusion at severe condition. Viscous behavior, verified by rheology analysis, showed marked differences between native and extruded samples. Extruded flours may be used as an ingredient for instant meal products. Native flour properties are comparable to those of isolated amaranth starch, which are good paste stability, low solubility in water, and elastic behavior. Thus, one of the commercial uses of thermoplastic extrusion is the production of instant meals.

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