Research Article

Chemical composition and physical properties of sorghum flour prepared from different sorghum hybrids grown in Argentina†

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Abbreviations

BD breakdown (PV −TV)
CD crystallinity degree
FV final viscosity
GOPOD glucose oxidase/peroxidase reagent
h_{ab} hue angle
PT pasting temperature
Pt peak time
PV peak viscosity
SB setback (FV – TV)
TV trough viscosity
WI whiteness index
WRC water retention capacity

Keywords
Chemical composition, pasting properties, sorghum flour, thermal properties.

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Abstract

This work analyzed the physical, chemical and thermal properties of sorghum flour and the relationships among these, in order to evaluate its suitability for the development of food products. Sorghum flour was obtained through roller dry milling from twenty commercial hybrids grown in Argentina with the average chemical composition of the samples being: 0.68 % ash, 3.67 % fat, 12.21 % protein, 83.45 % total carbohydrates, 79.77 % starch (amylose 26.6 %) and 34.9 mg of tannic acid per 100 g of flour. A high degree of variability among evaluated properties was found, particularly in the pasting properties peak viscosity (2809 - 5184 mPa s), breakdown (1169 - 3170 mPa s) and final viscosity (3030 to 4401 mPa s) with onset temperature (To) and gelatinization enthalpy (ΔH) varying between 66.8 and 72.6 °C, and 5.38 and 8.48 J/g, respectively. A Principal Component Analysis demonstrated that grain color did not influence the chemical composition of flour. Cluster analysis permitted the separation of flour into three different groups with different thermal and physicochemical characteristics, and enabled the selection of hybrids. Thus, sorghum flour is a versatile ingredient and can be used in several food and non-food applications.

Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is a grain rich in starch and polyphenolic compounds, and is the fourth most produced cereal in Argentina and the fifth in the world [1,2]. In the Western world, this grain is mostly used for animal feed, because its potential as an ingredient in the human diet has not yet been fully exploited. This crop has several good agronomic characteristics, being resistant to pests and diseases, showing plasticity concerning planting time, and being able to grow in arid areas, thus allowing a wide geographical distribution [3,4].

An increasing sorghum flour production has driven the development of different milling methods. Hammer milling with previous grain decortication and roller milling results in flours with lighter colors, and slightly less ash, tannin and fat [5,6]. Roller milling consists in a series of opposing pairs of rollers which break and reduce the grain endosperm, followed by sieving to separate most of the bran.

It has long been recognized that the functional properties of high-starch flour depend on a number of combined factors, of which some of the most relevant ones include starch content and composition, as well as protein content. The characterization of the flour is first necessary to achieve the desired functionality. Starch and starchy materials greatly contribute to the textural properties of many types of food and have numerous industrial applications as thickeners, colloidal stabilizers, gelling agents, bulking agents, water retention agents and adhesives [5,7]. Of particular interest to the food industry are new value-added products, resulting from many studies on the morphological, rheological, thermal and textural properties of various starch sources. Sorghums contain phenolic acids and most contain flavonoids [8], but only hybrids with a pigmented testa have condensed tannins, although some of these tannin sorghums are excellent antioxidants which slow hydrolysis in foods and increase the dietary fiber levels of food products [9], tannins constitute an antinutritional factor for monogastric animals due to reduction in proteins and starch digestibility [10].

Raw material characteristics and product quality are closely related with respect to food production [11]. Hence, the characterization of commercially available hybrids of sorghum is required to be able to choose those with the most suitable properties for each application, with the most important selection criteria used for grain sorghum by breeders being the direct measurement of grain yield and grain yield stability. Although selection is commonly based on performance trials across a wide number of sites and year [12], further characterization of sorghum hybrids is essential to fully develop their potential.

This investigation is part of a broader project aimed at adding value to the production of sorghum in the central region of Argentina. The systematic study of different hybrids grown in this region permits their characterization in order to determine the most suitable ones for particular uses in the food industry and for the production of native and modified starches. The objective of the present study was to evaluate the chemical composition and the thermal and physical characteristics of sorghum flour produced from twenty commercial hybrids, which then made, it is possible to acquire a better understanding of their properties and, thus be able to select appropriate sorghum flours to suit the characteristics of food ingredients.

Materials and methods

Materials

In conjunction with a local sorghum milling company (Amylum S.A.), we selected twenty high-yielding commercial sorghum hybrids from the central region of Argentina (2013),. White, red and brown grains were analyzed (Table 1) before being were cleaned and dry milled on a roller mill (Agromatic AG AQC 109, Laupen, Switzerland) and then sieved through a 60 mesh screen (250 µm) to separate most of the bran and comply with the regulations established by the *Codex Alimentarius* [13]. All reagents used were of analytical grade.

Proximal analysis

The determination of ash, fat, protein (N x 6.25) and total carbohydrates (TC) was carried out by standard methods [14].

Total starch and amylose content

The total starch and amylose content were determined by the method of Gibson *et al.* [15], using an amylose/amylopectin assay kit (K-Amyl, Megazyme International Ireland Ltd., Ireland). Flour was dispersed by heating in dimethyl sulfoxide (DMSO), and gelatinized starch was precipitated with ethanol (95 % v/v) and then separated by centrifugation. The supernatant was discarded, and the pellet was suspended in DMSO and acetate buffer solution. In one aliquot, the total starch was hydrolyzed to D-glucose and the amount determined using glucose oxidase/peroxidase reagent (GOPOD). In another aliquot, amylopectin was precipitated by concanavalin A (Con A) and removed by centrifugation, with the amylose content being determined by GOPOD.

Total polyphenols

Total polyphenol content (TP) was quantified using the Prussian blue assay, as described by Finocchiaro et.al [16] with some modifications. Sorghum flour (100 mg) was extracted for 1 h with 3 mL of 1 M NaOH in 15 mL centrifuge tubes, and were added to the extracts 3 mL of distilled water, 1 mL of 0.016 M $K_3Fe(CN)_6$ and 1 mL of 0.02 M $FeCl_3$. The mixture was stirred in a vortex for 10 s and allowed to stand for 15 min. Then, 3 mL of 6 M H_3P0_4 was added followed by 2 mL of 1% acacia gum (51198 SIGMA, SIGMA-ALDRICH Co, USA) 2 min later, and the mixture stirred in the vortex. Absorbance was measured at 700 nm using a spectrophotometer (Lambda 35, Perkin Elmer, USA), with the calibration curve being obtained using increasing concentrations (from 0 to 90 μg mL^{-1}) of tannic acid (403040 SIGMA, SIGMA-ALDRICH Co, USA) and verifying linearity (R^2 = 0.996). The total polyphenols were then expressed as mg of tannic acid per 100 g of dry flour.

Color

The color of the sorghum flour was determined using a colorimeter with a D65 illuminant at a 10 ˚ observation (CM-600d; Konica Minolta, Japan), with the results being expressed using CIELAB parameters (*L*, a*, b**). The color of the samples was compared through the whiteness index (*WI*) and hue angle (h_{ab}) utilizing equations 1 and 2, respectively [17], where WI indicates how near the sample is to an ideal white (WI = 100) and h_{ab} indicates the chromaticity (0°, red; 90°, yellow; 180°, green; 270°, blue).

$$WI = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \qquad (1)$$

$$h_{ab} = \tan^{-1}\left(\frac{b^*}{a^*}\right)^2 \qquad (2)$$

Water retention capacity

Water retention capacity (WRC) was determined following the method of Rodríguez-Sandoval *et al.* [18], and this index was used to characterize the behavior of flour in water systems. Sorghum flour samples (Pm, 500± 5 mg dry basis) were weighed and placed in 15 mL centrifuge tubes, after which 6 mL of water was added followed by incubation at 25 ºC for 30 minutes, with shaking carried out at 0, 10, 20 and 30 minutes. The tubes were then centrifuged for 20 min at 3000 x *g* before being inverted on absorbent paper in order to drain the excess liquid. The gel was weighed (Pg) and WRC was calculated as follows:

$$WRC = \frac{Pg}{Pm} \quad (3)$$

X-ray diffraction analysis

The crystal structure of the sorghum flour was analyzed using an X-ray diffractometer (Miniflex 600, Rigaku, Japan), with radiation produced by an X-ray tube (Philips PW3830, Cu K_{α}, Ni filter with a 0.5 mm aperture, voltage 45 kV and current 15 mA). A D-tex ultra-high speed detector was used to obtain diffraction patterns of high quality in a short time scanning was performed from 2 to 60 ° with a step size of 0.01 ° and a rate of 5 ° min^{-1}. The crystalline and amorphous areas were quantified through diffractogram deconvolution using Peakfit software v4 (Peakfit, Jandel Scientific, San Rafael, USA). The crystallinity degree (CD) was calculated as the intensity ratio of the crystalline/amorphous phases and expressed as a percentage.

Thermal properties

The thermal analysis of samples was carried out using a differential scanning calorimeter (DSC 823e, Mettler Toledo, Switzerland), with thermograms being evaluated by STARe software (V 9.00, Mettler Toledo, Switzerland). Flour samples (10 mg db) were weighed and placed into 100 μL aluminum pans with 20 μL of deionized water. These pans were then hermetically sealed and allowed to stand for 24 h at room temperature before heating in DSC, using a program beginning at 20 ºC and reaching 120 ºC at a heating rate of 10 ºC/min. An empty and sealed pan was used as a reference for all measurements. Thermal transitions were characterized through the onset temperature (*To*), peak temperature (*Tp*), conclusion temperature (*Tc*) and gelatinization enthalpy (*ΔH*), with the latter expressed in J/g of flour.

Pasting properties

The pasting properties of sorghum flour were determined using a Rapid Viscosity Analyzer (RVA 4500, Perten Instruments, Australia). To carry out the assay, 3.5 g of each sample

(14% moisture basis) were suspended in 25 g of distilled water and placed into the aluminum canisters.

The pasting properties were analyzed using the RVA standard profile with some modifications. Dispersions were stirred at 960 rpm for 10 s followed by constant stirring at 160 rpm until the end of the assay, with the temperature being maintained at 50 ºC for 1 minute, increased to 95 ºC at minute 5 and maintained for 2.5 minutes, cooled to 50 ºC in 3 minutes, and finally held at 50 ºC for 2 minutes. Thermocline for Windows© software (V 3.15, Perten Instruments, Australia) was used to obtain the pasting parameters, which included pasting temperature (PT, onset temperature at moment of increase in viscosity), peak viscosity (PV, maximum hot-paste viscosity), peak time (Pt), trough viscosity (TV, lowest viscosity when maintained at 95 ºC) and final viscosity (FV, viscosity at the end of the assay). Other parameters calculated were breakdown (BD=PV−TV) and setback (SB=FV–TV). Food grade corn starch (Maizena®, Argentina) was used as a reference.

Statistical analysis

All assays were performed at least in duplicate. The analysis of variance (ANOVA, multiple comparison test by Fisher, α=5 %), Pearson's correlation coefficients (r) and multivariate analysis (cluster analysis and principal component analysis, PCA) were performed using InfoStat software (Di Rienzo *et al.,* 2011). All graphs were obtained using Excel software (Office Version 2016, Microsoft) and InfoStat.

Results and Discussion

Chemical composition

Table 1 shows the chemical composition of sorghum flour, where it can be observed that there were found significant differences among the hybrids of sorghum flour, with ash content varying from 0.27 to 1.03 % (db) for DK51 and PbCr, respectively. In contrast, Liu *et al.* [20] and Winger *et al.* [21] reported higher values for ash content (around 1.4 % db) in decorticated sorghum flour. Several authors have found that sorghum flour with a low ash content has better baking properties [5,22], and in the present study no samples exceeded the 1.5 % ash limit established by the *Codex Alimentarius* [13].

Fat values ranged from 1.70 to 5.73 % (db) with an average value encountered of 3.67 % (db). This mean value is in agreement with the literature, although only half the samples comply with the limits recommended by the *Codex Alimentarius* [13].

The lowest protein content was in Dk51 (8.47 % db) and the highest in Ag61 (17.08 % db) with an average value of 12.21 % (db). This mean content was higher than that reported elsewhere for sorghum flour [20,21], but was close to that of whole grain [23]. Protein content plays an important role in human nutrition, especially sorghum proteins, since sorghum flour is safe for celiac patients and allows palatable, reasonably priced and nutritious foods to be developed [24]. The total carbohydrates content was between 77.02 and 88.99 % (db) with an average value of 83.45 % (db). In addition, the average total starch value was 79.77 % (db) with levels found between 71.84 and 85.14 % (db). This mean starch value is in agreement with others reported in the literature. Here, the samples presented a lower starch content than endosperm, but higher than whole grain [5], with this difference in starch content probably resulting from grain behavior during milling. Finally, the amylose content varied from 24.1 to 29.8 % (Table 1), which are normal values for sorghum grains [5,25], with only the lowest (Ag61) and highest (Pa87) values revealing significant differences with the other samples. Some correlations with this parameter are discussed below.

Of the sorghum phytochemicals, mainly tannins, phenolic acids and anthocyanins have the potential to have a considerable impact on human health [8]. The total polyphenols were quantified and the results were expressed in mg of tannic acid per 100 g of flour (Table 1), with values ranging from 16.8 to 79.6 and with an average of 34.9 mg of tannic acid. No correlation was found between white and colored sorghum samples in TP, and all values were lower than those reported by other authors in whole grain flour [26,27], as the *Codex*

Alimentarius establishes that tannin content in sorghum flour should not exceed 0.3% (db) (300 mg of tannic acid in 100 g of flour), then, all samples complied with this regulation.

Color

The average values for L^*, a^* and b^* were 84.94, 2.55 and 9.12, respectively, which were similar to those reported by Hidalgo *et al.* [28]. Additionally, no significant differences were found among flours from white (Ar12, BIJo and Pa87) and colored grain, a result that might be related to the low number of external layers (responsible for grain color) in the sorghum flour samples.

Whiteness Index values ranged from 74.0 to 84.5 (Table 2) and displayed significant differences among samples. In agreement with Subramanian *et al.* [29], who reported on isolated sorghum starches, the WI exhibited a negative correlation with protein content and TP ($p < 0.05$, $r = -0.65$ and -0.60, respectively). As the WI is a major characteristic of many foods, then the flour obtained in this study could be used when high whiteness is desirable, but this implies lower protein and polyphenol contents.

Regarding the hue angle (Table 2), the values found were in the red/yellow quadrant and showed an average value of 74.2 with a range between 55.0 and 89.1, which indicates that yellowness is the most important chromatic characteristic of sorghum flour. This finding may have been due to the presence of a larger proportion of yellow horny endosperm [23].

Water retention capacity

Differences in WRC values are related to the presence of hydrophilic compounds. Here, sorghum flour showed a diversity in the WRC values, ranging from 2.33 to 3.09 with an average of 2.70 (Table 3). Related to this, protein content presented a positive correlation with WRC ($p < 0.05$, $r = 0.71$), with the slight variation observed possibly due to kafirins (prolamins), a major sorghum protein, having a weak interaction with water [5]. Furthermore, there was a negative correlation between WRC and AM ($p < 0.05$, $r = -0.48$), and consequently, samples with more amylopectin presented higher WRC, which may be explained by the formation of hydrogen bonds permitted by the branched structure, molecular size and chain distribution of amylopectin [30].

X-ray diffraction analysis

Sorghum flour displayed an A-type XRD pattern (Fig. 1), similar to that of most cereal starches. This pattern exhibited main reflections at 2θ 15° and 23° and a doublet at 17° and 18° [23], with the XRD spectrum revealing crystalline and amorphous regions of starch. The proportion of crystalline and amorphous regions is one of the factors that indicates how rapidly starch can be hydrolyzed, which is essential for many sorghum starch and flour applications [31,32].

The sorghum flour studied in this work had different CD, ranging from 29.9 to 34.0 %,which were in general, higher than those reported by Sun *et al.* [33] for sorghum flour or Boudries *et al.* [32] for isolated sorghum starch. These results might be associated with the amylopectin content, the extension of amylopectin chains, or simply the evaluation method [25]. Although, Boudries *et al.* [32] reported differences in the CD between white and red sorghum starch, in the present work no significant differences were noted among red, white and brown flour.

Thermal properties

The thermal properties of starches are highly variable and determined by the arrangement of their crystalline region, which is influenced by genetic and environmental factors [32,34]. Fig. 2 displays the thermograms of representative samples, revealing well-defined endotherms that correspond to the gelatinization of starch, whit the enthalpy of gelatinization and its transition temperatures showing variations among samples. Table 3 displays the *ΔH* and *To* values, as well as the maximum, minimum and average values obtained in this work. The values of *ΔH* observed were consistent with those of Algerian sorghum starch and Chinese sorghum flour [33,35], with the average and maximum values found in this investigation (7.33 J/g and 8.48 J/g, respectively) being similar, although the minimum (5.38 J/g) was lower than those reported by Boudries *et al.* [32] and Sun *et al.* [33]. These variances could have been related to differences in the molecular structure of amylopectin, the amylose to amylopectin ratio, crystalline to amorphous ratio, granule shape or the percentage of large and small granules [36]. In fact, as the CD showed a slight variation among samples, differences in ΔH values were mainly attributed to amylose, starch and protein content. Amylose was positively correlated with ΔH ($p < 0.05$, $r = 0.56$), which could have resulted from endothermic granule swelling. Furthermore, the protein content displayed a negative correlation with ΔH ($p < 0.05$, $r = -0.55$), due to the dilution effect on starch concentration and potential competition with starch for available water.

The average of gelatinization temperatures (To = 69.0 ºC, Tp = 74.0 ºC and Tc = 81.7 ºC) were higher than those reported by Sun *et al.* [33] and Boudries *et al.* [32],which indicates a higher stability of the starch crystallites. In addition, no significant differences were found between white and pigmented sorghum gelatinization temperatures, with their range ($Tc - To$) being 12.6 °C. This value was higher than the 5.7 ºC reported by Sun *et al.* for sorghum flour [33], and also the 10.2 °C and 8.6 ºC reported by Boudries *et al.* [32] for white and red sorghum starches, respectively. A high range of gelatinization temperatures indicates heterogeneity of ordered structures inside starch granules and/or heterogeneity in their population.

Pasting properties

Table 3 summarizes the RVA parameters of samples, and Fig. 3 displays the pasting profiles of representative samples, which achieve a wide range. Of these, Pb81 revealed the highest PV (5185 mPa s) and Ag11 the lowest (2809 mPa s); FV varied from 3030 to 4402 mPa s; BD had a range between 1169 and 3171 mPa s and SB values between 1376 and 1968 mPa s. In contrast, Pt (data not shown) and PT presented similar values for all samples, with average values of 4.7 min and 74.0 ºC, respectively. Although the average values for all pasting parameters of the sorghum flour analyzed were similar to those reported for other sorghum flour [33], they were markedly different from another whole grain sorghum flour study [35]. Pasting properties determine the suitability of ingredients for several foods. Thus, as Dk51 revealed a similar pasting profile to that of corn starch (Fig. 3), it could therefore be a possible alternative to commercial corn starch.

Viscosity parameters were determined mainly by starch properties, and a positive correlation between starch content and PV ($p < 0.05, r = 0.60$) and BD values ($p < 0.05, r = 0.75$) was observed. It is known that an increase in viscosity is attributed to two main processes of granule swelling and amylose lixiviation. Hence, PV exhibited a positive correlation with amylose content ($p < 0.01, r = 0.56$), because a higher amount of amylose was able to leach and consequently increase the medium viscosity. Peak viscosity also presented a negative correlation with protein content ($p < 0.05, r = - 0.82$), as a result of the lower proportion of starch in rich protein samples, in addition to protein encapsulation around starch granules hindering water uptake and swelling [37]. The extent of SB reflects the starch retrogradation through the interaction between chains and the formation of aggregates. Here, as fat content presented a negative correlation with SB ($p < 0.05, r = - 0.45$), the lipids may have produced less compact gels and therefore resulted in a lower viscosity.

Some pasting properties were highly correlated with other pasting properties. Related to this, Shewayrga *et al.* [35] reported analogous relationships.

Pasting curves (Fig. 3) showed the usual viscosity profile of starchy cereal flours and similar curve shapes were found among samples. In the present study DSC, properties were correlated with pasting properties, with PT and To presenting a strong correlation ($p < 0.01, r = 0.84$). The PT was higher than To in all samples, which could be explained by the fact that To indicates the start of amylopectin swelling and PT is the temperature of onset of the rise in viscosity due to granule disruption. Since pasting properties are dependent on granule rigidity and ΔH depends on crystallinity [38], then some positive correlations were found. Here, sorghum flour thermal properties revealed the positive correlations: ΔH with PV ($p < 0.05$, $r = 0.52$) and ΔH with BD ($p < 0.05$, $r = 0.49$).

Sorghum flour has potential ingredients for use in food development, e.g., in noodle formulations. Flours with high FV and TV values can be used to improve the quality of noodles and increase elasticity [39]. Furthermore, pasting properties are central for regulating the viscosity behavior during the processing and storage of several food systems.

Multivariate analysis

Multivariate analysis is often used as a method of data screening in order to gain a better understanding of the structure and variables under study. A PCA was performed using the chemical compositions shown in Table 1, which revealed that the first two components accounted for 68.1 % (PC1 41.4 % and PC2 26.7 %) of the variation among the samples, with a cophenetic correlation of 0.933. The bi-plot of PC1 vs PC2 (Fig. 4) displays the relationships of sample distribution and the measured parameters. Samples are represented by colored dots according to sorghum grain color (Table 1) and the selected properties are represented by triangles. The PCA bi-plot reveals the variability in chemical composition parameters. Component 1 was defined by TP, fat and protein content along the positive axis, with the negative axis PC1 being described by starch, AM, TC and ash content.

A cluster analysis was applied to assess if the samples could be grouped according to the parameters measured. This was performed using the chemical composition with Ward's clustering algorithm and Euclidean distance, with the cluster number arbitrarily set to 3. An analysis of variance was applied between cluster groups, with the results indicating that the clusters differed in several parameters (Table 4). Fig. 4 also shows the clusters over the PCA bi-plot. Cluster 1 included Ag10, Ag11, Ag61, ArS8, ArS9 and PiAl and was typified by low ash, TC, starch, AM, PV, BD, FV, SB, ΔH and To, as well as high protein, fat, WRC and WI. Cluster 2 was typified by high values of TC, WRC, FV and WI, and low values for the other parameters. Cluster 2 included Ar12, Ar38, ArMa, ArPa, Dk51 and Pa87 samples, with cluster 3 including the remaining samples and was characterized by high values of fat, protein and WRC, and low values for the other parameters. Samples were not grouped by sorghum grain color, because this characteristic was not relevant for choosing flour with the desired properties.

Summing up, the results showed that the different sorghum flours studied could be separated into groups according to selected properties. The selection of an appropriate sorghum flour to suit particular food products requires an exhaustive study concerning the performance of each group and its effects on different food matrixes. The grouping of samples in the present study represents the first step to meeting this objective.

Conclusions

The thermal properties of flour, mainly those ofpasting parameters, exhibited a considerable variability which could be useful for selecting hybrids with potential commercial interest. A multivariate analysis indicated that this variability was strongly influenced by chemical composition, principally protein and starch content. Furthermore, it was shown that the color of sorghum grain had no influence on the chemical composition or the thermal behavior of the flour obtained. A cluster analysis was able to group sorghum flour into three clusters with differing characteristics. Consequently, the selection of hybrids could be made through the pasting profile or chemical composition. These results provide a background for further studies promoting sorghum industrialization. As most of the flour obtained complied with the *Codex Alimentarius* regulation it was suitable to be used in the food industry.

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Figures legends

Fig.1: X-ray diffraction pattern of sorghum flour samples with minimum and maximum crystallinity degrees (PiAl and ArPa, respectively).

Fig. 2: DSC thermograms of sorghum flour samples with minimum and maximum ΔH (Ag11 and PbCr, respectively).

Fig. 3: Pasting curves for selected sorghum flour and commercial corn starch.

Fig. 4: PCA bi-plot showing sample variation and cluster groups. Triangles and connectors show variables and dots indicate samples (dot colors indicate color of sorghum grain).

Fig.1: X-ray diffraction pattern of sorghum flour with minimum and maximum crystallinity degrees (PiAl and ArPa, respectively).

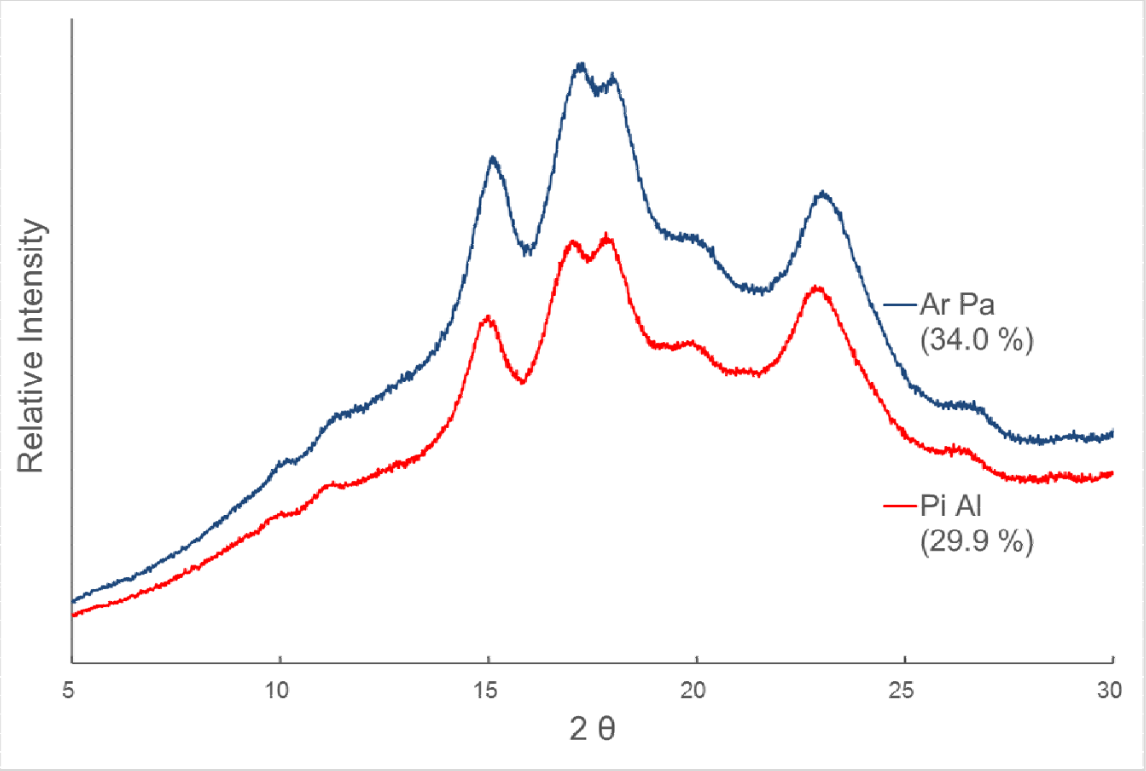


Fig. 2: DSC thermograms of sorghum flour with minimum and maximum *ΔH* (Ag11 and PbCr respectively).

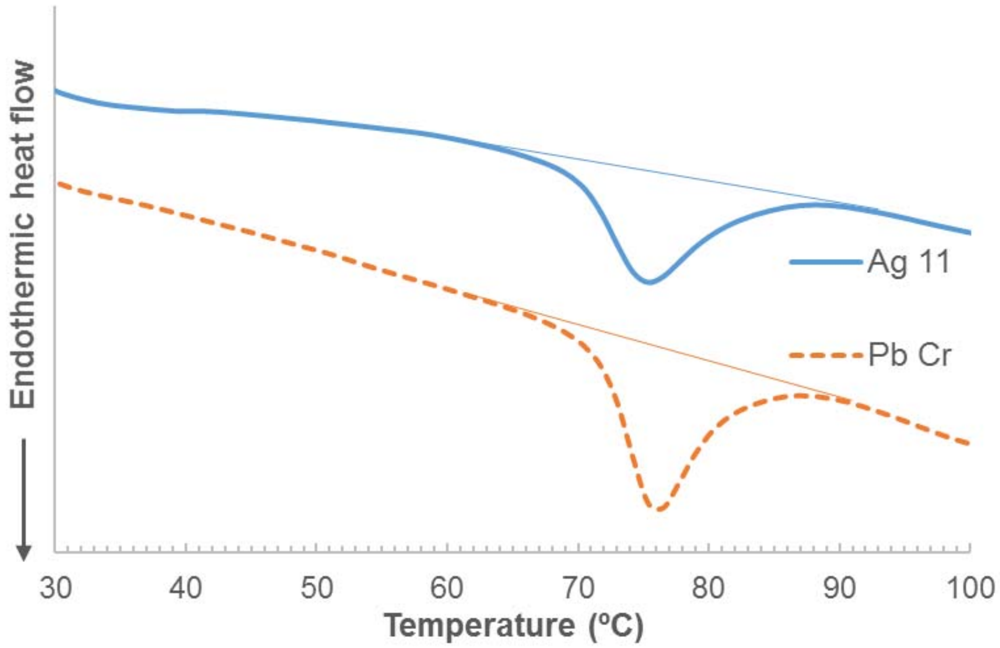


Fig. 3: Pasting curves for selected sorghum flour and commercial corn starch.

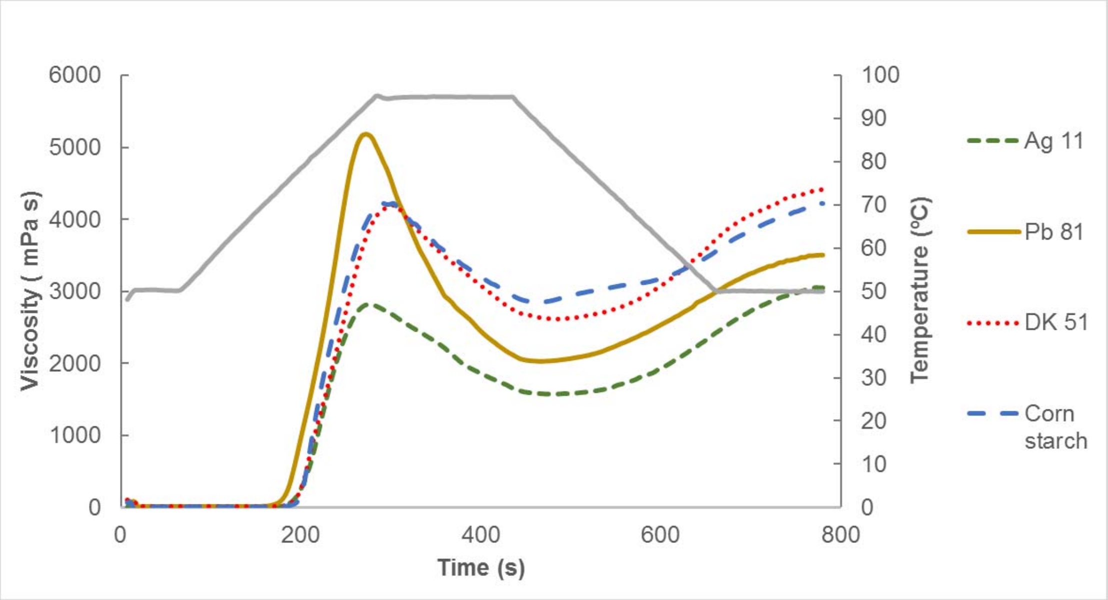
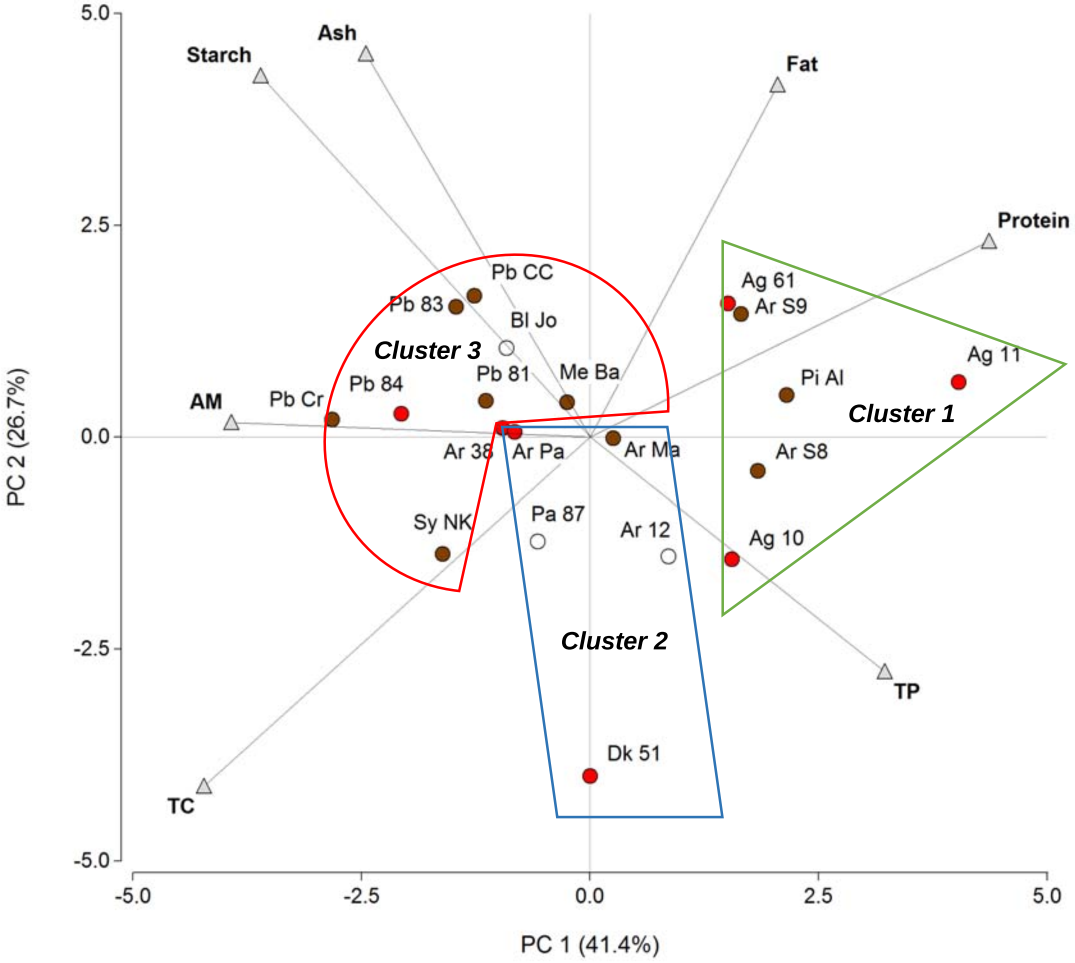


Fig. 4: PCA bi-plot showing sample variation and cluster groups. Triangles and connectors show variables and dots indicate samples (dot colors indicate color of sorghum grain).



TC: Total carbohydrates, TP: total polyphenols (expressed as mg of tannic acid in 100 g of flour).

Table 1. Proximate and chemical compositions of sorghum flour obtained from several sorghum hybrids grown in Argentina.

Sorghum	*Sample code*	*Grain color*	*Ash (%)*	*Fat (%)*	*Protein (%)*	*TC (%)*	*Starch (%)*	*AM (%)*	*TP*
Neogen-SAC100	Ag10	Red	0.48^{de}	2.66^{de}	12.86^{h}	84.00	77.47^{cd}	27.1^{b}	55.2^{k}
Neogen-SAC110	Ag11	Red	0.75^{h}	5.35^{jk}	16.89^{j}	77.02	74.70^{bc}	26.6^{b}	79.6^{m}
Neogen-SAC610	Ag61	Red	0.98^{k}	2.92^{e}	17.08^{k}	79.02	79.11^{de}	24.1^{a}	24.2^{e}
Argenetics-Argensor125B	Ar12	White	0.51^{e}	2.47^{cd}	12.72^{g}	84.29	74.18^{ab}	27.0^{b}	25.8^{e}
Argenetics-110T	ArS8	Brown	0.46^{d}	4.95^{hi}	12.77^{g}	81.82	77.46^{cd}	25.1^{ab}	53.6^{k}
Argenetics-130T	ArS9	Brown	0.49^{de}	5.37^{jk}	15.22^{i}	78.92	74.94^{bc}	28.0^{bc}	21.0^{cd}
Argenetics-Malon	ArMa	Brown	0.46^{d}	3.01^{e}	13.55^{gh}	82.98	81.29^{de}	28.3^{bc}	18.2^{ab}
Argenetics-Paisano	ArPa	Red	0.69^{g}	2.05^{ab}	12.67^{g}	84.59	82.94^{ef}	27.1^{b}	16.8^{a}
Dupont-Arvales382	Ar38	Red	0.70^{g}	4.38^{f}	9.63^{bc}	85.29	82.57^{ef}	25.7^{ab}	32.5^{g}
Nuseed-Joward Food	BlJo	White	0.92^{j}	4.83^{gh}	10.34^{cd}	83.91	83.12^{ef}	26.0^{ab}	31.8^{g}
Dekalb-Dk51	DK51	Red	0.27^{a}	2.27^{bc}	8.47^{a}	88.99	71.84^{a}	27.2^{b}	63.2^{l}
Low tannin mixture	MeBa	Brown	0.71^{gh}	4.57^{fg}	11.48^{e}	83.25	80.51^{de}	24.9^{ab}	32.8^{g}
Pannar-8706 W	Pa87	White	0.58^{f}	1.70^{a}	12.33^{f}	85.39	77.30^{cd}	29.8^{c}	22.3^{d}
Pioneer-80T25	PiAl	Brown	0.35^{b}	5.73^{k}	14.95^{i}	78.97	78.80^{de}	27.2^{b}	50.8^{j}
Pioneer-84G62	Pb84	Red	0.95^{j}	2.06^{ab}	10.85^{e}	86.14	85.14^{f}	25.3^{ab}	29.3^{f}
Pioneer-81G67 (Concept)	Pb81	Brown	0.87^{i}	4.30^{f}	9.96^{cd}	84.86	83.40^{ef}	25.2^{ab}	45.3^{i}
Pioneer-83G19 (Concept)	Pb83	Brown	0.93^{j}	5.28^{ij}	10.38^{d}	83.41	83.30^{ef}	27.3^{b}	19.6^{bc}
Pioneer-83G19 (Cruiser)	PbCr	Brown	1.03^{k}	2.64^{d}	9.07^{b}	87.26	82.90^{ef}	26.4^{ab}	17.3^{a}
Pioneer-83G19 (Cru-Con)	PbCC	Brown	0.94^{j}	5.08^{i}	11.35^{e}	82.63	82.60^{ef}	25.8^{ab}	17.2^{a}
Syngenta-NK240	SyNK	Brown	0.43^{cd}	1.79^{a}	11.62^{e}	86.16	81.90^{e}	28.0^{bc}	40.7^{h}
Average			*0.68*	*3.67*	*12.21*	*83.45*	*79.77*	*26.6*	*34.9*

Means with different letters within the same column indicate significant differences among samples ($p < 0.05$).

TC: Total carbohydrates, TP: total polyphenols (expressed as mg of tannic acid in 100 g of flour).

Table 2: Color parameters of sorghum flour obtained from several sorghum hybrids grown in Argentina.

Sample	L^*	a^*	b^*	*WI*	h_{ab}
Ag10	81.4^{b}	3.0^{h}	8.5^{c}	79.3^{bc}	70.3^{de}
Ag11	76.9^{a}	6.8^{j}	9.7^{de}	74.0^{a}	55.0^{a}
Ag61	82.6^{c}	3.5^{i}	10.0^{f}	79.6^{c}	70.5^{e}
Ar12	86.8^{h}	1.8^{d}	8.5^{c}	84.2^{h}	78.3^{i}
ArS8	86.7^{h}	2.3^{e}	9.7^{ef}	83.4^{e}	68.2^{c}
ArS9	86.7^{gh}	2.3^{e}	9.4^{de}	83.5^{fg}	76.8^{h}
ArMa	86.1^{fg}	2.5^{f}	9.4^{de}	83.1^{g}	79.3^{j}
ArPa	84.7^{e}	2.1^{e}	8.2^{b}	82.5^{fg}	75.5^{g}
Ar38	86.1^{f}	1.8^{d}	9.5^{de}	83.1^{fg}	75.3^{g}
BlJo	88.1^{i}	0.0^{a}	11.5^{h}	83.5^{g}	89.6^{l}
DK51	86.8^{h}	1.8^{d}	8.5^{c}	84.2^{h}	78.3^{i}
MeBa	83.5^{d}	3.1^{h}	8.4^{bc}	81.2^{d}	69.5^{de}
Pa87	87.0^{h}	0.5^{b}	11.2^{g}	82.8^{ef}	87.6^{k}
PiAl	87.0^{h}	1.6^{c}	8.4^{a}	84.5^{b}	79.4^{j}
Pb84	86.7^{h}	3.1^{h}	7.7^{bc}	84.3^{d}	76.2^{gh}
Pb81	84.0^{d}	3.1^{h}	8.4^{bc}	81.7^{h}	69.9^{de}
Pb83	87.1^{h}	3.1^{i}	7.7^{c}	84.3^{h}	75.8^{b}
PbCr	87.1^{e}	2.2^{e}	8.6^{b}	82.5^{e}	66.0^{gh}
PbCC	81.3^{b}	2.8^{g}	9.5^{de}	78.9^{h}	73.7^{f}
SyNK	82.3^{c}	3.6^{i}	9.7^{de}	79.5^{c}	69.4^{d}
Average	*84.9*	*2.5*	*9.1*	*82.0*	*74.2*

Means with different letters within the same column indicate significant differences among samples ($p < 0.05$).

L^*, a^* and b^*: CIELAB color parameters; *WI:* Whiteness index; h_{ab}: hue angle.

Table 3: Water retention capacity and XRD, DSC and RVA parameters.

Sample	*WRC*	*CD (%)*	*DSC*		*RVA (mPa s)*					
			ΔH (J/g)	*To (ºC)*	*PV*	*TV*	*BD*	*FV*	*SB*	*PT (ºC)*
Ag10	2.91^{hi}	32.1^{c}	7.07^{c}	72.6^{f}	3039^{c}	1715^{c}	1324^{bc}	3415^{e}	1700^{h}	75.8^{f}
Ag11	3.10^{i}	33.4^{f}	5.38^{a}	69.8^{d}	2809^{a}	1554^{ab}	1256^{b}	3042^{a}	1489^{bc}	75.1^{def}
Ag61	2.71^{ef}	33.3^{f}	7.12^{c}	67.4^{ab}	2886^{b}	1509^{ab}	1377^{cd}	3030^{a}	1521^{cd}	74.7^{de}
Ar12	2.79^{g}	32.7^{d}	6.87^{bc}	69.8^{d}	2910^{b}	1741^{cd}	1169^{a}	3709^{h}	1968^{j}	75.1^{def}
ArS8	2.79^{g}	32.7^{d}	6.93^{c}	70.1^{d}	3447^{f}	1924^{g}	1523^{e}	3300^{b}	1376^{a}	73.0^{ab}
ArS9	2.76^{fg}	30.8^{a}	6.86^{bc}	67.5^{ab}	3422^{ef}	1776^{d}	1646^{g}	3323^{bc}	1548de	72.2^{a}
ArMa	2.80^{g}	34.1^{g}	6.81^{c}	67.4^{ab}	3775^{g}	1840^{f}	1936^{i}	3414^{e}	1575^{e}	72.6^{ab}
ArPa	2.69^{e}	33.0^{e}	7.29^{bc}	68.2^{b}	3794^{g}	1940^{g}	1855^{h}	3524^{f}	1585^{ef}	72.6^{ab}
Ar38	2.58^{cd}	31.7^{b}	7.06^{bc}	67.2^{ab}	4306^{j}	1945^{g}	2361^{k}	3533^{f}	1588^{ef}	74.4^{cd}
BlJo	2.61^{de}	32.2^{c}	8.00^{cd}	66.8^{a}	4255^{ij}	1956^{g}	2299^{k}	3548^{f}	1592^{ef}	73.0^{ab}
DK51	2.68^{e}	32.8^{d}	7.25^{c}	71.0^{e}	4156^{h}	2596^{l}	1560^{ef}	4402^{k}	1806^{i}	75.4^{ef}
MeBa	2.63^{de}	32.9^{e}	7.82^{cd}	68.8^{c}	3796^{g}	1600^{b}	2196^{j}	3056^{a}	1456^{b}	74.3^{cd}
Pa87	2.84^{gh}	32.5^{cd}	6.90^{bc}	68.8^{c}	3493^{f}	1869^{f}	1624^{fg}	3629^{g}	1760^{i}	73.4^{bc}
PiAl	3.07^{i}	31.8^{b}	8.09^{cd}	67.4^{ab}	3233^{d}	1830^{ef}	1404^{d}	3348^{bc}	1518^{cd}	74.2^{cd}
Pb84	2.39^{ab}	31.4^{b}	7.93^{d}	71.4^{e}	4198^{hi}	1838^{f}	2360^{k}	3364^{cd}	1526^{cd}	73.1^{ab}
Pb81	2.55^{c}	32.7^{d}	8.05^{cd}	68.2^{b}	5185^{k}	2014^{h}	3171^{k}	3516^{f}	1502^{cd}	72.2^{a}
Pb83	2.51^{b}	33.6^{fg}	8.46^{b}	70.3^{d}	4507^{l}	2176^{j}	2331^{m}	3848^{j}	1672^{gh}	75.0^{def}
PbCr	2.33^{a}	32.7^{d}	8.48^{d}	71.4^{e}	4561^{k}	2227^{i}	2334^{k}	3819^{i}	1592^{ef}	75.1^{de}
PbCC	2.59^{d}	29.9^{a}	6.49^{cd}	69.9^{d}	4569^{k}	2066^{k}	2503^{l}	3769^{j}	1703^{h}	74.7^{def}
SyNK	2.75^{fg}	32.2^{c}	7.81^{cd}	68.7^{c}	3365^{e}	1785de	1581^{fg}	3410de	1626^{fg}	74.7^{de}
Average	*2.70*	*32.4*	*7.33*	*69.1*	*3785*	*1895*	*1890*	*3500*	*1605*	*74.0*
Minimum	*2.33*	*29.9*	*5.38*	*66.8*	*2809*	*1509*	*1169*	*3030*	*1376*	*72.2*
Maximum	*3.10*	*34.1*	*8.48*	*72.6*	*5185*	*2596*	*3171*	*4402*	*1968*	*75.8*

Means with different letters within the same column indicate significant differences among samples ($p < 0.05$).

WRC: water retention capacity; CD: crystallinity degree; ΔH: enthalpy of gelatinization; To: temperature of onset; PV: peak viscosity; TV: trough viscosity; BD: breakdown (PV −TV);

FV: final viscosity; SB; setback (FV – TV); PT: pasting temperature.

Table 4: Properties of sorghum flour samples grouped by cluster analysis.

Cluster	*Ash (%)*	*Fat (%)*	*Protein (%)*	*TC (%)*	*Starch (%)*	*AM (%)*	*WRC*	*PV (mPa s)*	*BD (mPa s)*	*FV (mPa s)*	*SB (mPa s)*	*ΔH (J/g)*	*WI*
1	0.59^{a}	4.50^{b}	14.96^{b}	79.96^{a}	78.08^{a}	25.38^{a}	2.89^{b}	3139^{a}	1422^{a}	3243^{a}	1525^{a}	6.91^{a}	79.6^{a}
2	0.50^{a}	2.30^{a}	11.95^{a}	85.25^{b}	77.50^{a}	26.22^{a}	2.76^{b}	3625^{a}	1629^{a}	3735^{b}	1584^{a}	7.02^{ab}	83.6^{b}
3	0.83^{b}	3.88^{a}	10.52^{a}	84.77^{b}	82.82^{b}	27.63^{b}	2.55^{a}	4304^{b}	2348^{b}	3540^{ab}	1739^{b}	7.79^{b}	82.8^{b}

Means with different letters within the same column indicate significant differences among samples ($p < 0.05$).

WRC: water retention capacity; PV: peak viscosity; BD: breakdown (PV −TV); FV: final viscosity; SB; setback; ΔH: enthalpy of gelatinization; WI: whiteness index.