Food Chemistry 119 (2010) 95–100

Contents lists available at ScienceDirect

Food Chemistry

journal homepage: www.elsevier.com/locate/foodchem

Characterisation of starches separated from sorghum cultivars grown in India

Harinder Singh [a], Navdeep Singh Sodhi [a,b,*], Narpinder Singh [a]

[a] Department of Food Science and Technology, Guru Nanak Dev University, Amritsar 143 005, Punjab, India
[b] Food Physics Laboratory, Food Function Division, National Food Research Institute, 2-1-12 Kannondai, Tsukuba, Ibaraki 305-8642, Japan

ARTICLE INFO

Article history:
Received 19 March 2009
Received in revised form 23 April 2009
Accepted 28 May 2009

Keywords:
Sorghum starch
Physico-chemical
Morphological
Thermal
Retrogradation
Pasting
Texture

ABSTRACT

Starches from 15 Indian sorghum cultivars were separated and evaluated for physicochemical, morphological, thermal, retrogradation, pasting and textural properties. The morphological characterisation revealed the presence of irregular-polyhedral as well as spherical shaped granules. A wide variation in amylose content ranging from 11.2% to 28.5% was observed. Thermal, retrogradation, pasting and textural characteristics also showed significant differences amongst all the starch cultivars. Principal component analysis was carried out to extract five principal components that could explain 75% of the total variance. The first two principal components PC1 (T_o, T_p, T_c and ΔH_{gel}) and PC2 (amylose content, range of gelatinisation, PHI and pasting and textural properties) could explain a cumulative variance of 44%, indicating the importance of amylose, thermal and textural properties on the sorghum starch functionality.

1. Introduction

Sorghum (*Sorghum bicolor* (L.) Moench), a member of grass family, is the fifth leading cereal crop used throughout the world after wheat, rice, maize and barley (Suhendro, McDonough, Rooney, Wanishka, & Yetneberk, 1998). It is also referred to as "coarse grain" or "poor people crop" as it can sustain the lives of the poorest rural people (www.fao.org). It is grown in the arid and semi-arid regions of the world (Murty & Kumar, 1995) and is an important cereal due to its extensive drought resistance and requirement of relatively lower inputs (Watson, 1970) and hence called 'Life Saver' (www.fao.org). As more than 500 million people in the developing countries depend on sorghum as the main staple food (Mutisya, Sun, Rosenquist, Baguma, & Jansson, 2009) so relevant scientific information generated for this crop can certainly play a key role in agricultural development in these countries of the world (Palmer, 1992).

Starch, nature's most abundant polysaccharide, is a major food reserve providing energy often at a low cost in the human diet and having diverse applications both in food and non-food industries. These days the availability of corn to the Indian starch industry is decreasing day by day because of its increased demand by industries involved in the production of breakfast cereals, snacks, etc. As sorghum, like other cereals, is rich in starch (approximately 70%) and has excellent potential for industrial applications (Zhan et al., 2003) it can be exploited for starch production. It is wet-milled similarly to corn for starch manufacture (Subramanian, Hoseney, & Bramel-Cox, 1994) and is technically equivalent to corn starch in its functionality (Freeman & Watson, 1971). As India produces 7.24×10^6 metric tons of sorghum per annum and stands as the third largest producer in the world (www.fao.org) so there is enough potential in this crop to be utilised as a starch source. Keeping this in view, the present work was undertaken and starch was isolated from various sorghum cultivars and evaluated to access its possibility as a potential raw material for the Indian food industry.

2. Materials and methods

2.1. Materials

Sorghum cultivars (SPV-824, CSV-14, CSV-16, CSH-16, M-35, IM-9B, SPV-669, CSV-13, Swathi, CSH-18, B-27, CSV-15, SPV-839, CSV-216, SPV-462) were procured from National Research Centre for Sorghum (NRCS), Hyderabad. SPV-669 was procured from Punjab Rao Deshmukh University, Akola, Maharashtra. All the seeds on manual examination had white pericarp. The seeds were tested for condensed tannins as described by Xie and Seib (2002). Sorghum kernels (15 g) were stirred in highly alkaline (7.5 g potassium hydroxide) sodium hypochlorite (5%) solution (70 ml) at 60 °C for

* Corresponding author. Address: Department of Food Science and Technology, Guru Nanak Dev University, Amritsar 143 005, Punjab, India. Tel.: +91 183 2258802x3430; fax: +91 183 2258820.
E-mail addresses: navdeep@affrc.go.jp, navdeep_fst@yahoo.co.in (N.S. Sodhi).

0308-8146/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.foodchem.2009.05.086

7 min. Kernels turned light yellow indicating that the seeds were free from tannins.

2.2. Methods

2.2.1. Starch isolation

Starch was extracted by using the method of Beta, Corke, Rooney, and Taylor (2000). Sorghum grain (100 g) was steeped in 200 ml of NaOH (0.25%, w/v) at 5 °C for 24 h. The steeped grains were washed and ground with an equal volume of water using a blender for 3 min. The slurry was filtered through a 200-mesh screen. The material remaining on the sieve was rinsed with water. Grinding and filtering were repeated on this material. After rinsing, the material still remaining on the sieve was discarded. The filtrate was allowed to stand for 1 h. The filtrate was centrifuged at 760*g* for 10 min. The grey coloured, top protein-rich layer was removed using a spatula. Excess water was added to re-suspend the sample, and centrifugation was done for 5 min. Washing and centrifugation were repeated several times until the top starch layer was white. The starch was dried for 24 h at 40 °C.

2.2.2. Amylose content, swelling power and solubility

Amylose content was determined by the method of Williams, Kuzina, and Hlynka (1970). Swelling power and solubility of starches were determined using method of Leach, McCowen, and Schoch (1959).

2.2.3. Morphological properties

Scanning electron micrographs of native starches were obtained with a scanning microscope (Jeol JSM-6100, Jeol Ltd., Tokyo, Japan). Starch samples were suspended in ethanol to obtain a 1% suspension. One drop of the starch–ethanol solution was applied to an aluminium stub, and the starch was coated with gold–palladium (60:40). An acceleration potential of 10 kV was used during micrography.

2.2.4. Thermal properties

Thermal properties of native starches were analysed using a DSC-821e (Mettler Toledo, Switzerland) equipped with a thermal analysis data station. Starch (3.5 mg, dwb) was weighed in an aluminium pan of 40 μl capacity (Mettler, ME-27331). Distilled water was added with the help of a Hamilton micro syringe to achieve a starch–water suspension of (30:70). Samples were hermetically sealed and allowed to stand for 1 h at room temperature before heating in DSC. The DSC analyser was calibrated using indium and an empty aluminium pan was used as reference. Sample pans were heated at a rate of 10 °C/min from 35 to 100 °C. Onset temperature (T_o), peak temperature (T_p), conclusion temperature (T_c) and enthalpy of gelatinisation (ΔH_{gel}) were calculated automatically. Because the peaks were symmetrical the gelatinisation range (R) was computed as ($T_c - T_o$) as described by Vasanthan and Bhatty (1996). Enthalpies were calculated on starch dry basis.

After conducting thermal analysis, the samples were stored in the refrigerator at 4 °C for 7 days for retrogradation studies. The sample pans were reheated at a rate of 10 °C/min from 35 to 100 °C after 7 days to measure retrogradation. The enthalpy of retrogradation (ΔH_{ret}) was evaluated automatically and the percentage retrogradation (%R) was calculated as the ratio of the enthalpy of retrogradation to the enthalpy of gelatinisation multiplied by 100. All the measurements were repeated three times.

2.2.5. Pasting properties

The pasting properties of starches were evaluated with a Rapid Visco Analyser (RVA-4, Newport Scientific, Warriewood, Australia). Starch (3 g, 14% moisture basis) was weighed directly into the aluminium RVA sample canister, and distilled water was added to make the total constant sample weight of 28 g. A programmed heating and cooling cycle was used where the samples were held at 50 °C for 1 min, heated to 95 °C in 3.7 min, held at 95 °C for 2.5 min before cooling to 50 °C in 3.8 min, and then held at 50 °C for 2 min. Parameters recorded were pasting temperature (PT); peak viscosity (PV); hot paste viscosity (HPV) (minimum viscosity at 95 °C); final viscosity (FV) (final viscosity at 50 °C); breakdown (BD) (=PV−HPV); and set back (SB) (=CPV−HPV). All measurements were replicated thrice.

2.2.6. Textural properties

Textural properties of RVA starch gels (Bhattacharya, Zee, & Corke, 1999) were evaluated using the TA/XT2 Texture Analyser (Stable Micro Systems, Surrey, England). The starch slurry formed in the canister after RVA testing was covered and kept at 4 °C overnight and allowed to gel. The gel formed in the can (37 mm diameter, 20 mm height) was used directly for texture analysis. The gels equilibrated to room temperature (≈25 °C) were compressed to a distance of 10 mm using a flat cylindrical probe (5 mm dia.) at a cross-head speed of 30 mm/min. The textural parameters of hardness, cohesiveness, springiness, gumminess and chewiness were computed using textural profile analysis (TPA). The average of twelve repeated measurements was reported.

2.2.7. Statistical analysis

The data reported are an average of triplicate observations except for textural properties. The data were subjected to ANOVA, and differences between means were located with Tukey's multiple comparison test ($p < 0.05$). The main variance in the data was detected with multivariate analysis using Principal Component Analysis (PCA). Minitab Release 15 Statistical Software (Minitab Inc., State College, PA) was used for carrying out the statistical analysis.

3. Results and discussion

3.1. Physico-chemical properties

The amylose content of starches isolated from different sorghum cultivars ranged between 11.2% and 28.5% (Table 1). SPV-462 showed the highest amylose content (28.5%) followed by CSV-216 (26%) and SPV-839 (25.9%). Gaffa et al. (2004) reported an amylose content of 25.5% for starches isolated from various Nigerian sorghum cultivars. Sang, Bean, Seib, Pedersen, and Shi (2008) observed amylose content of 23.7, 14.0 and 0%, respectively

Table 1
Amylose content, solubility, and swelling power of starches from different sorghum cultivars.[A]

Cultivars	Amylose content (%)	Solubility (%)	Swelling power (g/g)
SPV-824	11.2^{a}	7.0^{a}	9.2^{a}
CSV-14	15.0^{b}	11.0^{cd}	15.3^{d}
CSV-16	17.4^{cd}	7.8^{a}	14.0^{cd}
CSH-16	17.6^{d}	19.0^{f}	15.0^{d}
M-35	18.7^{de}	11.9^{d}	6.2^{a}
IM-9B	19.7^{de}	7.4^{b}	10.5^{b}
SPV-669	20.1^{de}	6.0^{a}	14.0^{cd}
CSV-13	20.7^{e}	5.3^{a}	9.3^{a}
Swathi	21.5^{e}	6.5^{ab}	9.0^{a}
CSH-18	21.9^{e}	15.2^{e}	11.0^{bc}
B-27	23.2^{ef}	9.2^{bc}	10.3^{b}
CSV-15	24.5^{fg}	16.2^{e}	10.0^{a}
SPV-839	25.9^{g}	13.0^{d}	7.0^{a}
CSV-216	26.0^{gh}	5.0^{a}	12.2^{b}
SPV-462	28.5^{h}	9.0^{bc}	11.8^{bc}

[A] Values with similar superscripts in a column do not differ significantly ($p < 0.05$).

for normal, heterowaxy and waxy sorghum starches. Starches isolated from all genotypes in the present study were white in colour and seeds were free from tannins as tested using sodium hypochlorite. The ability to swell in excess water and solubility of the starches from various cultivars differed significantly (Table 1). Swelling power (SP) and solubility provide evidence of the magnitude of the interaction between starch chains within both the amorphous and crystalline domains (Singh, Singh, Kaur, Sodhi, & Gill, 2003). CSH-16 starch showed the highest solubility (19%) whereas CSV-216 starch showed the lowest solubility (5.0%). SP of starches from different sorghum cultivars ranged between 6.2 and 15.3 g/g, being the highest for CSV-14 and the lowest for M-35. Subrahmanyam and Hoseney (1995) reported SP between 13.8 and 15.2 g/g and solubility between 17.4% and 22.5% for starches isolated from seven US sorghum cultivars. Olayinka, Adebowale, and Olu-Owolabi (2008) reported SP of 8.79 g/g and solubility of 5% for Nigerian sorghum starch. Genetic and environmental factors as well as starch isolation procedure may be attributed to the differences in the swelling power and solubility of sorghum starches.

3.2. Morphological properties

The scanning electron micrographs showed the presence of irregular-polyhedral as well as spherical granules (Fig. 1). The granules of starches separated from the majority of cultivars showed the presence of pores as reported earlier by Huber and BeMiller (2000) and Benmoussa, Suhendra, Aboubacar, and Hamaker (2006). M-35 starch showed the presence of doughnut-shaped granules. The tube-like channels were also observed in granules of starches from the majority of cultivars. Benmoussa et al. (2006) reported round, polygonal and "doughnut-shaped" morphology for sorghum starch granules. Huber and BeMiller (2000) observed that radial, tube-like channels of sorghum starch granules penetrate from the external surface inward toward a cavity at the hilum. These channels, however, were reported to vary in depth of penetration from granule to granule. Fannon, Shull, and BeMiller (1993) hypothesised these pores of sorghum and millet starches as the openings to channels that provide access to the granule interior.

3.3. Thermal properties

The results of DSC analysis of starches separated from different sorghum cultivars are shown in Table 2. The transition temperatures T_o, T_p, and T_c ranged between 66.1 and 73.12 °C, 70.1 and 77.79 °C and 75.0 to 81.24 °C, respectively. The enthalpy of gelatinisation (ΔH_{gel}) of starches from different sorghum cultivars ranged between 9.26 and 13.5 J/g. CSH-18 starch showed the highest T_o, T_p, and T_c and ΔH_{gel}. Subrahmanyam and Hoseney (1995) reported a ΔH_{gel} between 2.84 and 3.39 J/g for seven US sorghum starches. Sang et al. (2008) observed T_o, T_p, and T_c and ΔH_{gel} of 67.9, 70.7,

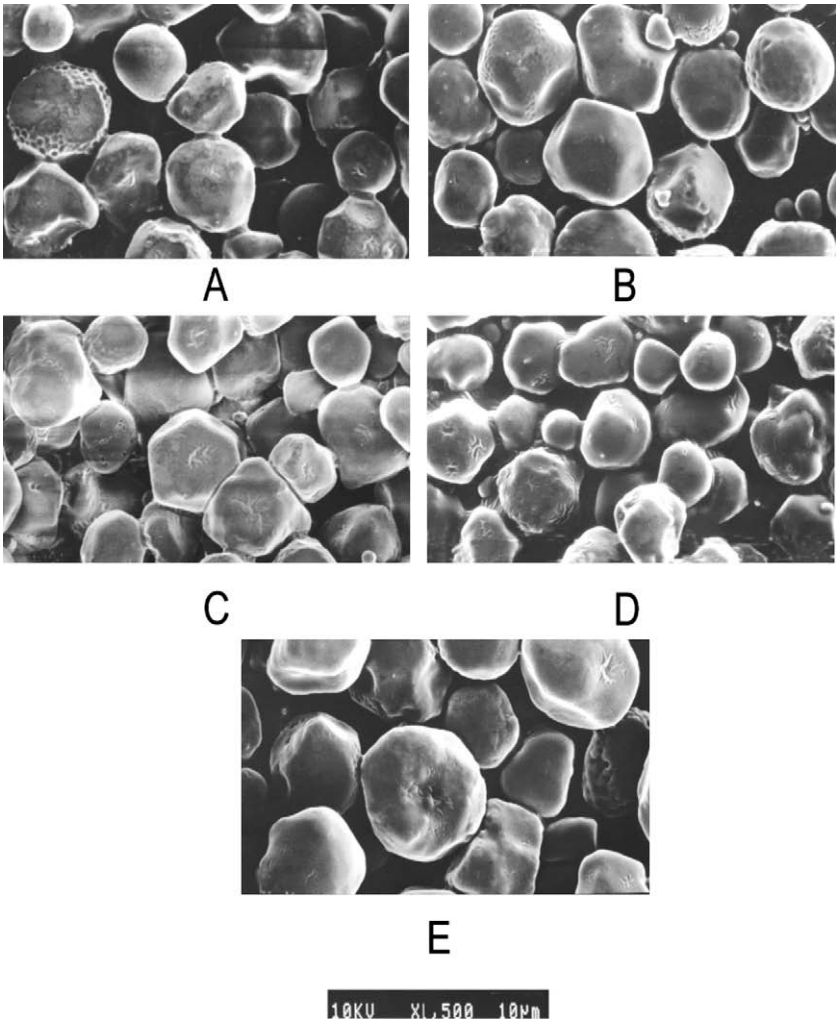

Fig. 1. Typical scanning electron micrographs (SEM) of sorghum starches (A: CSV-16, B: B-27, C: SPV-42, D: CSH-16, E: M-35).

Table 2
Thermal properties of starches separated from different sorghum cultivars.[A]

Cultivars	T_o (°C)	T_p (°C)	T_c (°C)	ΔH_{gel} (J/g)	R (°C)	PHI
SPV-824	72.01^{f}	75.69^{f}	79.94^{f}	13.22^{d}	7.93^{b}	3.59^{b}
CSV-14	68.17^{c}	73.33^{cd}	76.28^{b}	13.13^{d}	8.11^{c}	2.54^{a}
CSV-16	66.10^{a}	70.50^{a}	75.40^{a}	9.37^{a}	9.30^{d}	2.13^{a}
CSH-16	72.13^{f}	75.85^{ef}	79.82^{f}	12.50^{c}	7.69^{b}	3.36^{ab}
M-35	68.40^{c}	72.10^{b}	76.16^{b}	11.47^{b}	7.76^{b}	3.11^{ab}
IM-9B	71.84^{e}	74.59^{de}	77.42^{d}	11.75^{b}	5.58^{a}	4.27^{c}
SPV-669	68.59^{cd}	72.86^{c}	77.26^{cd}	11.90^{b}	8.67^{c}	2.79^{a}
CSV-13	71.96^{ef}	74.89^{e}	78.48^{e}	12.76^{c}	6.52^{a}	4.35^{c}
Swathi	68.89^{cd}	72.43^{bc}	77.38^{d}	9.82^{a}	8.49^{c}	2.77^{a}
CSH-18	73.12^{g}	77.79^{g}	81.24^{g}	13.50^{d}	8.12^{c}	2.89^{a}
B-27	71.94^{ef}	74.92^{e}	78.82^{e}	11.12^{b}	6.88^{a}	3.73^{b}
CSV-15	71.48^{e}	74.04^{d}	77.44^{d}	12.70^{c}	5.96^{a}	4.96^{c}
SPV-839	69.09^{d}	72.69^{c}	76.83^{c}	11.30^{b}	7.74^{b}	3.14^{ab}
CSV-216	66.74^{b}	70.10^{a}	75.0^{a}	9.26^{a}	8.25^{c}	2.76^{a}
SPV-462	69.37^{d}	72.36^{bc}	76.17^{b}	12.19^{c}	6.80^{a}	4.08^{c}

T_o = onset temperature; T_p = peak temperature; T_c = conclusion temperature; ΔH_{gel} = enthalpy of gelatinisation; R = gelatinisation range ($T_c - T_o$), PHI = peak height index $\Delta H_{gel}/(T_p - T_o)$.

[A] Values with similar superscripts in a column do not differ significantly ($p < 0.05$).

75.7 °C and 13.2 J/g, respectively for normal sorghum starch. Beta et al. (2000) observed an average T_p of 67.4 °C and ΔH_{gel} of 7.45 J/g for ten Zimbabwean sorghum starches. Gaffa et al. (2004) reported a T_c of 90 °C and ΔH_{gel} of 13.7 J/g for Nigerian sorghum starch. Significant positive correlations of ΔH_{gel} with T_o ($r = 0.703$, $p \leqslant 0.005$), T_p ($r = 0.787$, $p \leqslant 0.005$) and T_c ($r = 0.643$, $p \leqslant 0.05$) were observed. Peak height index (PHI) ranged from 2.13 (CSV-16) to 4.96 (CSV-15). The difference in gelatinisation ranges, (R) defined as difference between T_c and T_o amongst the starches from different cultivars was significant and ranged between 5.58 °C for IM-9B and 9.3 °C for CSV-16. Beta et al. (2000) reported a mean R value of 13.2 °C for ten Zimbabwean sorghum starches. The differences in the R values amongst the starches from different cultivars may be attributed to the presence of crystalline regions within a starch granule composed of small crystallites having slightly different crystal strength (Banks & Greenwood, 1975).

3.4. Retrogradation properties

The retrogradation properties of starch gels after seven days of refrigerated storages were measured using DSC (Table 3). T_o of retrograded starches ranged between 46.2 and 52.6 °C, the lowest for CSV-16 and the highest for SPV-669. T_p and T_c of retrograded starch gels ranged between 54.18 and 58.61 °C and 61.4 to 65.9 °C, respectively. The enthalpy of retrogradation (ΔH_{ret}) for the starches varied between 1.11 J/g for Swathi and 4.31 J/g for CSV-13. Significant positive correlations ($r = 0.568$, $p \leqslant 0.05$; $r = 0.623$, $p \leqslant 0.05$; $r = 0.651$, $p \leqslant 0.05$) between T_c of retrogradation and T_o, T_p and T_c of gelatinisation were observed, respectively. Transition temperatures and ΔH_{ret} of stored starch pastes were significantly lower than the transition temperatures of gelatinisation and ΔH_{gel} of starch dispersions. Morikawa and Nishinari (2000) reported that starch molecule recrystallisation occurs in a less ordered manner in stored starch gels than in native starches. A significant positive correlation ($r = 0.643$, $p \leqslant 0.05$) between ΔH_{ret} and ΔH_{gel} was observed. Sang et al. (2008) showed a T_o, T_p, and T_c of 41.8, 50.5 and 62.7 °C and ΔH_{ret} of 4.3 J/g for normal sorghum starch. The higher the ΔH_{ret} of a starch, the lower its tendency to retrograde. ΔH_{ret} is an indication of the unraveling and melting of double helices formed during storage, which is influenced by the amylopectin unit chain length distribution (Shi & Seib, 1992). The percentage retrogradation (%R) is defined as the ratio of ΔH_{ret} and ΔH_{gel} ranged between 11.3% and 33.78%, the lowest for Swathi and the highest for CSV-13. The retrogradation properties of the starch gels depend upon the structural arrangement of starch chains within the amorphous and crystalline regions of the ungelatinised granule, which in turn influences the extent of granule breakdown during gelatinisation and the interaction that occurs between starch chains during gel storage (Perera & Hoover, 1999).

3.5. Pasting properties

Pasting properties for starches from different cultivars are reported in Table 4. Peak viscosity (PV) varied between 2541 and 4698 cP, the highest for CSV-16 and the lowest for CSV-15. B-27 (4063 cP), M-35 (4072 cP), Swathi (3616 cP) also showed significantly higher PV as compared to starches from other cultivars. A significant negative correlation ($r = -0.593$, $p \leqslant 0.05$) of PV with ΔH_{gel} was observed. Hot paste viscosity (HPV) ranged between 919 and 2629 cP, the lowest for CSV-14 and the highest for IM-9B. The differences in HPV may be attributed to the difference in the extent of amylose leaching, amylose–lipid complex formation and granule swelling (Liu, Ramsden, & Corke, 1997). BD varied between 911 and 2645 cP. CSV-16 showed the highest BD of 2645 cP followed by 2401 cP of SPV-824 and 2100 cP of CSV-14. A significant negative correlation ($r = -0.573$, $p \leqslant 0.05$) of BD with amylose

Table 3
Retrogradation properties of starches from different sorghum cultivars.[A]

Cultivars	T_o (°C)	T_p (°C)	T_c (°C)	ΔH_{ret} (J/g)	% R
SPV-824	49.05^{bc}	57.60^{c}	65.38^{c}	3.41^{b}	25.79^{f}
CSV-14	48.21^{a}	55.31^{a}	62.55^{a}	2.80^{ab}	21.33^{d}
CSV-16	46.20^{a}	55.12^{a}	63.76^{b}	1.95^{a}	20.81^{d}
CSH-16	50.26^{cd}	56.95^{b}	65.90^{c}	1.78^{a}	14.24^{b}
M-35	49.75^{b}	56.29^{b}	62.33^{a}	2.38^{ab}	20.75^{d}
IM-9B	48.81^{bc}	56.44^{b}	64.91^{c}	2.90^{ab}	24.68^{e}
SPV-669	52.60^{d}	58.26^{c}	65.33^{c}	3.38^{bc}	28.40^{g}
CSV-13	48.8^{bc}	56.41^{b}	65.49^{c}	4.31^{c}	33.78^{h}
Swathi	46.28^{a}	54.18^{a}	62.39^{a}	1.11^{a}	11.30^{a}
CSH-18	49.18^{bc}	56.07^{a}	64.55^{c}	2.93^{ab}	21.70^{d}
B-27	48.21^{a}	56.41^{b}	63.45^{b}	3.47^{ab}	31.21^{h}
CSV-15	49.67^{bc}	55.96^{a}	62.90^{a}	2.32^{b}	18.27^{c}
SPV-839	51.82^{d}	58.61^{c}	64.72^{c}	2.19^{ab}	19.38^{c}
CSV-216	49.88^{bc}	55.50^{a}	61.40^{a}	1.15^{a}	12.42^{a}
SPV-462	47.61^{a}	54.62^{a}	62.14^{a}	3.03^{b}	24.86^{ef}

T_o = onset temperature; T_p = peak temperature; T_c = conclusion temperature; ΔH_{ret} = enthalpy of retrogradation; %R = percentage of retrogradation (ratio of enthalpy of retrogradation to enthalpy of gelatinisation).

[A] Values with similar superscripts in column do not differ significantly ($p < 0.05$).

Table 4
Pasting properties of starches isolated from various sorghum cultivars.[A]

Cultivars	PV (cP)	HPV (cP)	BD (cP)	FV (cP)	SB (cP)	PT (°C)
SPV-824	3503^{e}	1102^{b}	2401^{i}	3133^{d}	2031^{f}	80.9^{f}
CSV-14	3019^{c}	919^{a}	2100^{h}	2814^{c}	1895^{e}	77.5^{b}
CSV-16	4698^{h}	2053^{g}	2645^{i}	3238^{b}	1185^{a}	75.2^{a}
CSH-16	3254^{d}	2195^{g}	1059^{b}	3632^{g}	1437^{c}	80.7^{f}
M-35	4072^{g}	2396^{h}	1676^{f}	4120^{k}	1724^{d}	77.4^{cd}
IM-9B	3609^{f}	2629^{i}	980^{b}	4743^{e}	2114^{f}	79.5^{e}
SPV-669	3482^{e}	2066^{f}	1416^{e}	3535^{f}	1469^{c}	78.2^{d}
CSV-13	3264^{d}	2109^{g}	1155^{c}	3952^{j}	1843^{e}	80.0^{f}
Swathi	3616^{f}	1721^{e}	1895^{g}	3495^{f}	1773de	77.4^{c}
CSH-18	2804^{b}	2227^{h}	577^{a}	3981^{j}	1754de	80.3^{f}
B-27	4063^{g}	2147^{g}	1916^{g}	3824^{i}	1677^{d}	79.4^{e}
CSV-15	2541^{a}	1247^{c}	1294^{d}	2314^{a}	1067^{a}	76.0^{b}
SPV-839	3392^{e}	2009^{f}	1383^{d}	3741^{h}	1732^{d}	77.0^{c}
CSV-216	3213^{d}	2302^{h}	911^{b}	3390^{e}	1088^{a}	79.3^{e}
SPV-462	2698^{a}	1566^{d}	1132^{c}	2841^{c}	1275^{b}	77.5^{c}

PV = peak viscosity; HPV = hot paste viscosity; BD = breakdown viscosity; FV = final viscosity; SB = setback viscosity; PT = pasting temperature.

[A] Values with similar superscripts in a column do not differ significantly ($p < 0.05$).

content was observed. Higher BD in starches with a higher crystallinity and lower amylose content has been reported earlier (Singh, Inouchi, & Nishinari, 2006). The maximum viscosity at a given concentration indicates the ability of the granules to swell freely before physical breakdown. Higher PV of CSV-16, M-35 and B-27 starches may be attributed to the absence of lipids as confirmed by X-ray diffraction studies (data not shown). Final viscosity (FV) and setback (SB) of starches from different cultivars ranged between 2314 for CSV-15 and 4743 cP for IM-9B and 1067 cP for CSV-15 to 2114 cP for IM-9B, respectively. Beta et al. (2000) showed a mean PV, HPV, CPV, BD and SB of 3984, 1392, 2928, 2592 and 1536 cP, respectively for starches isolated from ten Zimbabwean sorghum cultivars. Gaffa et al. (2004) reported a PV, BD and SB of 2004, 144 and 1476 cP, respectively for Nigerian sorghum starch. PT varied between 75.2 and 80.9 °C. This corresponded well with T_c measured using DSC ($r = 0.709$, $p \leqslant 0.005$). The PT observed in our study was higher than the values (69–70.3 °C) reported earlier for Zimbabwean varieties (Beta et al., 2000). Gaffa et al. (2004) reported a PT of 82.6 °C for Nigerian sorghum starch. Genetic differences may have contributed to the differences in pasting properties of starches from different cultivars. The starch isolation procedure using alkali used in present study may also be responsible for the differences in the pasting and hydration properties of starches from those reported by other authors. The effect of polyphenolic compounds has been reported to be positively correlated to PV (Beta et al., 2000). Tannins may have no or little effect on the pasting properties of starches in this study, as tannins were not detected by qualitative determination.

3.6. Textural properties

The hardness of the starch gels ranged between 21.3 and 69.4 g (Table 5). SPV-824 starch gel was softer as compared to gels from other cultivars. SPV-462 starch gel showed the highest hardness of 69.4 g. The hardness values observed for starch gels in the present study are consistent with previously reported values of between 36.1 and 59.2 g for ten Zimbabwean sorghum starches (Beta et al., 2000). Cohesiveness for various starch gels ranged between 0.301 (M-35) and 0.636 (SPV-839). SPV-824, CSV-216 and SPV-669 starches showed higher cohesiveness as compared to starch gels from other cultivars. Adhesiveness ranged between 28.6 and 98 gs. SPV-839 starch showed the highest adhesiveness value and CSV-16 starch had the lowest value. Adhesiveness showed a negative correlation with SP ($r = -0.572$, $p \leqslant 0.05$). Springiness varied between 0.857 and 0.982. A significant negative correlation of springiness with SB ($r = -0.542$, $p \leqslant 0.05$), T_o ($r = -0.567$, $p \leqslant 0.05$), T_p ($r = -0.515$, $p \leqslant 0.05$) and T_c ($r = -0.554$, $p \leqslant 0.05$) were observed. Gumminess varied between 8.26 and 27.07 g. Gumminess was positively correlated to the amylose content of starches ($r = 0.538$, $p \leqslant 0.05$). Chewiness ranged between 8.06 and 25.09 g. Chewiness was also positively correlated with the amylose content of starches ($r = 0.544$, $p \leqslant 0.05$). The variations in mechanical properties of starch gels may be attributed to differences in the rheological characteristics of the amylose matrix, the volume fraction and rigidity of gelatinised starch granules as well as the interactions between dispersed and continuous phases of the gel (Biliaderis, 1998). These factors, in turn have been reported to depend on the amylose content and structure of amylopectin (Yamin, Lee, Pollak, & White, 1999).

3.7. Principal component analysis

Principal component analysis was carried out to find out the characteristics which mainly govern the functionality of sorghum starch. The eigenvalues of the 14 principal components could explain all the variances. The first five principal components accounted for 75% of the total variance. Eigenvector values were used to find out the meaning of each component. The first principal component (PC1) was mainly attributed to the thermal properties (T_o, T_p, T_c and ΔH_{gel}) and accounted for 28.2% of the total variance. Amylose content, PV, BD, hardness, adhesiveness, gumminess, chewiness, R and PHI were mainly associated with the second principal component (PC2) and accounted for 15.4% of the total variance. The third principal component (PC3) explained 12.4% of the variance and was influenced by HPV, FV and gel cohesiveness. The fourth principal component (PC4), which explained 9.9% of variance, was negatively influenced by gelatinisation temperatures of retrograded starch (T_o and T_p) of and gel springiness. The fifth principal component (PC5) was mainly associated with solubility, ΔH_{ret} and $\%R$ of retrograded starch and explained an additional 8.9% of the total variance.

4. Conclusion

The starches isolated from different sorghum cultivars showed significant differences in their functional properties indicating their suitability for diverse applications. Hence, their commercialisation may be exploited as per the requirements of the food industry and consumer preferences. Principal component analysis extracted five principal components that could explain 75% of the total variance. Furthermore, it is suggested that future studies on

Table 5
Textural properties of starches separated from different sorghum cultivars.[A]

Cultivars	Hardness (g)	Cohesiveness	Adhesiveness (gs)	Springiness	Gumminess (g)	Chewiness (g)
SPV-824	21.3^{a}	0.564^{d}	64.5^{d}	0.916^{b}	12.01^{a}	11.00^{ab}
CSV-14	39.8^{c}	0.427^{b}	40.0^{b}	0.950^{cd}	16.99^{b}	16.14^{cd}
CSV-16	31.0^{b}	0.457^{b}	28.6^{a}	0.970^{d}	14.17^{b}	13.74^{bc}
CSH-16	29.3^{b}	0.410^{b}	32.4^{a}	0.870^{ab}	12.01^{a}	10.45^{a}
M-35	49.3^{f}	0.301^{a}	41.9^{b}	0.940^{cd}	14.84^{b}	13.95^{bc}
IM-9B	39.4^{c}	0.395^{b}	65.2^{d}	0.890^{ab}	15.56^{b}	13.85^{bc}
SPV-669	31.4^{b}	0.503^{c}	41.7^{b}	0.982^{d}	15.79^{b}	15.51^{cd}
CSV-13	36.1^{c}	0.457^{bc}	84.0^{f}	0.912^{b}	16.50^{b}	15.05^{cd}
Swathi	47.0^{ef}	0.455^{b}	71.8^{e}	0.857^{a}	21.39^{c}	18.33^{d}
CSH-18	42.7^{de}	0.410^{b}	38.9^{b}	0.912^{b}	17.51^{b}	15.97^{c}
B-27	24.2^{ab}	0.500^{c}	58.9^{c}	0.870^{ab}	12.10^{a}	10.53^{a}
CSV-15	25.4^{ab}	0.325^{a}	84.0^{f}	0.976^{d}	8.26^{a}	8.06^{a}
SPV-839	37.0^{c}	0.636^{e}	98.0^{g}	0.930^{c}	23.53^{c}	21.88^{d}
CSV-216	35.8^{c}	0.562^{c}	85.1^{f}	0.975^{d}	20.12^{c}	19.62^{d}
SPV-462	69.4^{g}	0.390^{b}	58.9^{c}	0.927^{bc}	27.07^{d}	25.09^{e}

[A] Values with similar superscripts in column do not differ significantly ($p < 0.05$).

structural characterisation of sorghum starches to fully understand their functionality should be conducted.

Acknowledgements

The authors wish to thank Dr. N. Seetharama, Director, National Research Centre for Sorghum (NRCS), Hyderabad and Dr. S.B. Dakate, Punjabrao Deshmukh University, Akola for providing the sorghum seed samples for the present research. Research facilities provided by Regional Sophisticated Instrumentation Centre (RSIC), Panjab University, Chandigarh and Department of Chemical Engineering, Indian Institute of Technology (IIT), Delhi are also highly acknowledged.

References

Banks, W., & Greenwood, C. T. (1975). *In starch and its components* p. 121. Edinburgh, Scotland: Edinburgh University Press.

Benmoussa, M., Suhendra, B., Aboubacar, A., & Hamaker, B. R. (2006). Distinctive sorghum starch granule morphologies appear to improve raw starch digestibility. *Starch, 58*, 92–99.

Beta, T., Corke, H., Rooney, L. W., & Taylor, J. R. N. (2000). Starch properties as affected by sorghum grain chemistry. *Journal of the Science of Food and Agriculture, 81*, 245–251.

Bhattacharya, M., Zee, S. Y., & Corke, H. (1999). Physicochemical properties related to quality of rice noodles. *Cereal Chemistry, 76*, 861–867.

Biliaderis, C. G. (1998). Structures and phase transitions of starch polymers. In R. H. Walter (Ed.), *Polysaccharide association structures in foods* (pp. 57–168). New York, USA: Marcel Dekker Inc..

Fannon, J. E., Shull, J. M., & BeMiller, J. N. (1993). Interior channels of starch granules. *Cereal Chemistry, 70*, 611–613.

Freeman, J. E., & Watson, S. A. (1971). Influence of sorghum endosperm pigments on starch quality. *Cereal Science Today, 16*, 378–381.

Gaffa, T., Yoshimoto, Y., Hanashiro, I., Honda, O., Kawasaki, S., & Takeda, Y. (2004). Physicochemical properties and molecular structure of starches from millet (*Pennisetum typhoides*) and sorghum (*Sorghum bicolor* L. Moench) cultivars in Nigeria. *Cereal Chemistry, 81*, 255–260.

Huber, K. C., & BeMiller, J. N. (2000). Channels of maize and sorghum starch granules. *Carbohydrate Polymers, 41*, 269–276.

Leach, H. W., McCowen, L. D., & Schoch, T. J. (1959). Structure of the starch granule. I. Swelling and solubility patterns of various starches. *Cereal Chemistry, 36*, 534–544.

Liu, H., Ramsden, L., & Corke, H. (1997). Physical properties and enzymatic digestibility of acetylated *ae*, *wx*, and normal maize starch. *Carbohydrate Polymers, 34*, 283–289.

Morikawa, K., & Nishinari, K. (2000). Effects of concentration dependence of retrogradation behaviour of dispersions for native and chemically modified potato starch. *Food Hydrocolloids, 14*, 395–401.

Murty, D. S., & Kumar, K. A. (1995). Traditional uses of sorghum and millets. In D. A. V. Dendy (Ed.), *Sorghum and millets: Chemistry and technology* (pp. 185–221). St. Paul, MN: American Association of Cereal Chemists.

Mutisya, J., Sun, C., Rosenquist, S., Baguma, Y., & Jansson, C. (2009). Diurnal oscillation of SBE expression in sorghum endosperm. *Journal of Plant Physiology, 166*, 428–434.

Olayinka, O. O., Adebowale, K. O., & Olu-Owolabi, B. I. (2008). Effect of heat–moisture treatment on physicochemical properties of white sorghum starch. *Food Hydrocolloids, 22*, 225–230.

Palmer, G. H. (1992). Sorghum-food, beverage and brewing potentials. *Process Biochemistry, 27*, 145–153.

Perera, C., & Hoover, R. (1999). Influence of hydroxypropylation on retrogradation properties of native, defatted and heat moisture treated potato starches. *Food Chemistry, 64*, 361–375.

Sang, Y., Bean, S., Seib, P. A., Pedersen, J., & Shi, Y. C. (2008). Structure and functional properties of sorghum starches differing in amylose content. *Journal of Agricultural and Food Chemistry, 56*, 6680–6685.

Shi, Y. C., & Seib, P. A. (1992). The structure of four waxy starches related to gelatinization and retrogradation. *Carbohydrate Research, 227*, 131–145.

Singh, N., Inouchi, N., & Nishinari, K. (2006). Structural, thermal and viscoelastic characteristics of starches separated from normal, sugary and waxy maize. *Food Hydrocolloids, 20*, 923–935.

Singh, N., Singh, J., Kaur, L., Sodhi, N. S., & Gill, B. S. (2003). Morphological, thermal and rheological properties of starches from different botanical sources. *Food Chemistry, 81*, 219–231.

Subrahmanyam, S. N., & Hoseney, R. C. (1995). Shear thinning properties of sorghum starch. *Cereal Chemistry, 72*, 7–10.

Subramanian, V., Hoseney, R. C., & Bramel-Cox, P. (1994). Factors affecting the colour and appearance of sorghum starch. *Cereal Chemistry, 71*, 275–278.

Suhendro, E. L., McDonough, C. M., Rooney, L. W., Wanishka, R. D., & Yetneberk, S. (1998). Effects of processing conditions and sorghum cultivar on alkaline-processed snacks. *Cereal Chemistry, 75*, 187–193.

Vasanthan, T., & Bhatty, R. S. (1996). Physicochemical properties of small and large granule starches of waxy, regular, and high amylose barleys. *Cereal Chemistry, 73*, 199–207.

Watson, S. A. (1970). Wet Milling process and products. In J. S. Wall & W. M. Ross (Eds.), *Sorghum production and utilization* (pp. 602–626). Westport, CT: Avi.

Williams, P. C., Kuzina, F. D., & Hlynka, I. (1970). A rapid colorimetric procedure for estimating the amylose content of starches and flours. *Cereal Chemistry, 47*, 411–420.

Xie, X. J., & Seib, P. A. (2002). Laboratory wet milling of grain sorghum with abbreviated steeping to give two products. *Starch, 54*, 169–178.

Yamin, F. F., Lee, M., Pollak, L. M., & White, P. J. (1999). Thermal properties of starch in corn variants isolated after chemical mutagenesis of inbred line B73. *Cereal Chemistry, 76*, 175–181.

Zhan, X., Wang, D., Tuinstra, M. R., Bean, S., Seib, P. A., & Sun, X. S. (2003). Ethanol and lactic acid production as affected by sorghum genotype and location. *Industrial Crops and Products, 18*, 45–255.