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Some properties of corn starches II: Physicochemical, gelatinization, retrogradation, pasting and gel textural properties

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Abstract

The physicochemical, thermal, pasting and gel textural properties of corn starches from different corn varieties (African Tall, Ageti, Early Composite, Girja, Navjot, Parbhat, Partap, Pb Sathi and Vijay) were studied. Amylose content and swelling power of corn starches ranged from 16.9% to 21.3% and 13.7 to 20.7 g/g, respectively. The enthalpy of gelatinization (ΔH_{gel}) and percentage of retrogradation (%R) for various corn starches ranged from 11.2 to 12.7 J/g and 37.6% to 56.5%, respectively. The range for peak viscosity among different varieties was between 804 and 1252 cP. The hardness of starch gels ranged from 21.5 to 32.3 g. African Tall and Early Composite showed higher swelling power, peak, trough, breakdown, final and setback viscosity, and lower ΔH_{gel} and range of gelatinization. Pearson correlations among various properties of starches were observed. Gelatinization onset temperature (T_o) was negatively correlated to peak-, breakdown-, final- and setback viscosity ($r = -0.809, -0.774, -0.721$ and -0.686, respectively, $p < 0.01$) and positively correlated to pasting temperature ($r = 0.657, p < 0.01$). ΔH_{gel} was observed to be positively correlated with T_o, peak gelatinization temperature and (T_p) and gelatinization conclusion temperature T_c ($r = 0.900$, 0.902 and 0.828, respectively, $p < 0.01$) whereas, it was negatively correlated to peak- and breakdown- ($r = -0.743$ and -0.733, respectively, $p < 0.01$), final- and setback viscosity ($r = -0.623$ and -0.611, respectively, $p < 0.05$). Amylose was positively correlated to hardness ($r = 0.511, p < 0.05$) and gumminess ($r = 0.792, p < 0.01$) of starch gels.

Keywords: Corn starch; Physicochemical; Thermal; Pasting; Gel texture

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1. Introduction

Corn starch is a valuable ingredient to the food industry, being widely used as a thickener, gelling agent, bulking agent and water retention agent (Singh, Singh, Kaur, Sodhi, & Gill, 2003). In India, corn has become the third most important food grain after wheat and rice. The demand for corn is increasing in India with the setting up of food processing units involved in the processing of corn. The production of corn in India was 14,000,000 Mt against the total world production of 721,000,000 Mt (FAO, 2004).

On the basis of amylose and amylopectin ratio, corn can be separated into normal, waxy and high amylose. In addition, sugary type corn, with high sugar content, also exits (Singh, Sandhu, & Kaur, 2005). Normal starch consists of about 75 wt% branched amylopectin and about 25 wt% amylose, that is linear or slightly branched. Starch granules swell when heated in excess water and their volume fraction and morphology play important roles in the rheological behaviour of starch dispersions (Bagley & Christiansen, 1982; Da Silva, Oliveira, & Rao, 1997; Evans & Haisman, 1979). Starch retrogradation has been defined as the process, which occurs when the molecular chains in gelatinized starches begin to reassociate in an ordered structure (Atwell, Hood, Lineback, Varriano Marston, & Zobel, 1988). During retrogradation, amylose forms double-helical associations of 40–70 glucose units (Jane & Robyt, 1984) whereas amylopectin crystallization occurs by reassociation of the outermost short branches (Ring

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et al., 1987). Although both amylose and amylopectin are capable of retrograding, the amylopectin component appears to be more responsible for long-term quality changes in foods (Miles, Morris, Orford, & Ring, 1985; Ring et al., 1987). Several workers have characterized the pasting properties of starches from different corn types (Ji et al., 2003; Seetharaman et al., 2001; Yamin, Lee, Pollak, & White, 1999) and observed considerable variability in these properties. The viscosity parameters during pasting are cooperatively controlled by the properties of the swollen granules and the soluble materials leached out from the granules (Doublier, Llamas, & Meur, 1987; Eliasson, 1986). Sandhu, Singh, and Kaur (2004) studied the effect of corn types on the physicochemical, thermal, morphological and rheological properties of corn starches. Textural properties of starch gels are very important criteria, used to evaluate the performance of starch in a food system. Ji et al. (2003) used a texture analyzer for studying the gel properties of starches from selected corn lines and found significant differences among them. Seetharaman et al. (2001) studied the textural properties of 13 selected Argentinian corn landraces and found significant variability in hardness between them after storage. The objective of this study was to characterize the corn varieties grown in India on the basis of the physicochemical, thermal, pasting and gel textural properties of their starch. This will be useful in selecting the appropriate variety for end use suitability.

2. Materials and methods

2.1. Materials

Six improved corn varieties, viz., Ageti, Navjot, Parbhat, Partap, Pb Sathi and Vijay from the 2003 harvest were obtained from Punjab Agricultural University, Ludhiana, India. Three improved corn varieties, viz., African Tall, Early Composite and Girja from the 2003 harvest were obtained from Chaudhary Sarwan Kumar Himachal Pradesh Agricultural University, Palampur, India.

2.2. Starch isolation

Starch was isolated from corn grains following the method of Sandhu, Singh, and Malhi (2005).

2.3. Physicochemical properties of starch

2.3.1. Amylose content (%)

Amylose content of the isolated starch was determined by using the method of Williams, Kuzina, and Hlynka (1970). A starch sample (20 mg) was taken and 10 ml of 0.5 N KOH was added to it. The suspension was thoroughly mixed. The dispersed sample was transferred to a 100 ml volumetric flask and diluted to the mark with distilled water. An aliquot of test starch solution (10 ml) was pipetted into a 50 ml volumetric flask and 5 ml of 0.1 N HCL was added followed by 0.5 ml of iodine reagent. The volume was diluted to 50 ml and the absorbance was measured at 625 nm. The measurement of the amylose was determined from a standard curve developed using amylose and amylopectin blends.

2.3.2. Swelling power (g/g) and solubility (%)

Swelling power and solubility of starches were determined in triplicate using the method of Leach, McCowen, and Schoch (1959).

2.3.3. Turbidity

Turbidity of starch pastes from different corn varieties was measured as described by Perera and Hoover (1999). A 1% aqueous suspension of starch from each corn variety was heated in a water bath at 90 °C for 1 h with constant stirring. The starch paste was cooled for 1 h at 30 °C. The samples were stored for 5 days at 4 °C and turbidity was determined every 24 h by measuring absorbance at 640 nm against a water blank with a Shimadzu UV-1601 spectrophotometer (Shimadzu Corporation, Kyoto, Japan).

2.3.4. Water binding capacity (WBC)

WBC of the starches from the different corn varieties was determined using the method described by Yamazaki (1953), as modified by Medcalf and Gilles (1965). A suspension of 5 g starch (dry weight) in 75 ml distilled water was agitated for 1 h and centrifuged (3000*g*) for 10 min. The free water was removed from the wet starch, which was then drained for 10 min. The wet starch was then weighed.

2.4. Thermal properties of starches

The thermal characteristics of the isolated starches were studied by using a differential scanning calorimeter (DSC, model 821^e, Mettler Toledo, Switzerland), equipped with a thermal analysis data station. Starch (3.5 mg, dry weight) was loaded into a 40 μl capacity aluminium pan (Mettler, ME-27331) and distilled water was added by Hamilton microsyringe, to achieve a starch-water suspension containing 70% water. Samples were hermetically sealed and allowed to stand for 1 h at room temperature before heating in the DSC. The DSC analyzer was calibrated using indium and an empty aluminium pan was used as a reference. Sample pans were heated at a rate of 10 °C/min from 20 to 100 °C. Thermal transitions of starch samples were defined as T_o (onset temperature), T_p (peak of gelatinization temperature) and T_c (conclusion temperature) and ΔH_{gel} referred to the enthalpy of gelatinization. Enthalpies were calculated on a starch dry weight basis. These were calculated automatically. The gelatinization temperature range (R) and peak height index (PHI), was calculated as $2(T_p - T_o)$ and $\Delta H/(T_p - T_o)$, as described by Krueger, Knutson, Inglett, and Walker (1987). After conducting thermal analysis, the samples were stored at 4 °C for 7 days, for retrogradation studies. The sample pans containing the starches were reheated at the rate of 10 °C/min from 25 to 100 °C after 7 days to measure retrogradation. The enthalpies of retrogradation (ΔH_{gel}) were evaluated automatically and percentage of retrogradation (%R) was calculated as

$$\%R = \left(\frac{\text{enthalpy of retrogradation}}{\text{enthalpy of gelatinization}}\right) \times 100.$$

2.5. Pasting properties of starches

The pasting properties of the starches were evaluated with the Rapid Visco Analyzer (RAV-4, Newport Scientific, Warriewood, Australia). Viscosity profiles of starches from different corn varieties were recorded using starch suspensions (6%, w/w; 28 g total weight). A programmed heating and cooling cycle was used, where the samples were held at 50 °C for 1 min, heated to 95 °C at 6 °C/min, held at 95 °C for 2.7 min, before cooling from 95 to 50 °C at 6 °C/min and holding at 50 °C for 2 min. Parameters recorded were pasting temperature, peak viscosity, trough viscosity (minimum viscosity at 95 °C), final viscosity (viscosity at 50 °C), breakdown viscosity (peak-trough viscosity) and setback viscosity (final-trough viscosity). All measurements were replicated thrice.

2.6. Textural properties of starch gels

The starch prepared in the RVA were poured into small aluminum canisters and stored at 4 °C to cause gelation. The gel formed in the canisters was evaluated for their textural properties by texture profile analysis (TPA) using the TA/XT2 texture analyzer (Stable MicroSystems, Surrey, England). Each canister was placed upright on the metal plate and the gel was compressed at a speed of 0.5 mm/s to a distance of 10 mm with a cylindrical plunger (diameter = 5 mm). The compression was repeated twice to generate a force–time curve from which hardness (height of first peak) and springiness (ratio between recovered height after the first compression and the original gel height) was determined. The negative area of the curve during retraction of the probe was termed adhesiveness. Cohesiveness was calculated as the ratio between the area under the second peak and the area under the first peak (Bourne, 1968; Friedman, Whitney, & Szczesniak, 1968). Gumminess was determined by multiplying hardness and cohesiveness. Chewiness was derived from gumminess and springiness and was obtained by multiplying these two. Five repeated measurements were performed for each sample and their average was taken.

2.7. Statistical analysis

The data reported in all of the tables are an average of triplicate observations and were subjected to one-way analysis of variance (ANOVA). Pearson correlation coefficients (r) for the relationships between all properties were also calculated using Minitab Statistical Software version 13 (Minitab Inc., USA).

3. Results and discussion

3.1. Physicochemical properties of starches

Amylose content of starches from different corn varieties differed significantly (Table 1). Amylose content of various corn starches ranged between 16.9% and 21.3%, the lowest was observed for African tall and the highest for Vijay. Seetharaman et al. (2001) reported amylose content in the range of 16.1–23.3% for 35 corn landraces. The ability of starches to swell in excess water and their solubility also differed significantly (Table 1). Swelling power (SP) and solubility can be used to assess the extent of interaction between starch chains, within the amorphous and crystalline domains of the starch granule (Ratnayake, Hoover, & Warkentin, 2002). SP was observed to be the highest for Early Composite (20.7 g/g) and the lowest for Parbhat starch (13.7 g/g). Starch swelling occurs concomitantly with loss of birefringence and precedes solubilization (Singh, Sandhu, & Kaur, 2004). Solubility of various corn starches ranged from 9.7% to 15.0% (Table 1). Water binding capacity (WBC) of starches from different corn varieties ranged from 82.1% to 97.7% (Table 1). WBC of starches from Parbhat and Partap were similar (91.1%). The difference in the degree of availability of water binding sites among the starches may have contributed to the variation in WBC among different starches (Wotton & Bamunuarachchi, 1978). The turbidity values of gelatinized starch suspensions from different corn varieties are depicted in

Table 1
Physicochemical properties of starches from different corn varieties

Variety	Amylose content (%)	Swelling power (g/g)	Solubility (%)	WBC (%)
African Tall	16.9a	19.4d	13.5c	84.9ab
Ageti	19.4c	16.8bc	15.0d	82.3a
Early Composite	17.9b	20.7e	12.6bc	90.5c
Girja	16.9a	17.8c	11.3b	82.1a
Navjot	19.6c	14.9ab	11.6b	97.7d
Parbhat	19.5c	13.7a	10.1a	91.1c
Partab	18.5b	13.8a	9.7a	91.1c
PbSathi	20.9d	15.9b	12.0bc	86.0b
Vijay	21.3d	16.8bc	13.9c	83.0ab

Values with similar letters in the same column do not differ significantly ($p < 0.05$).

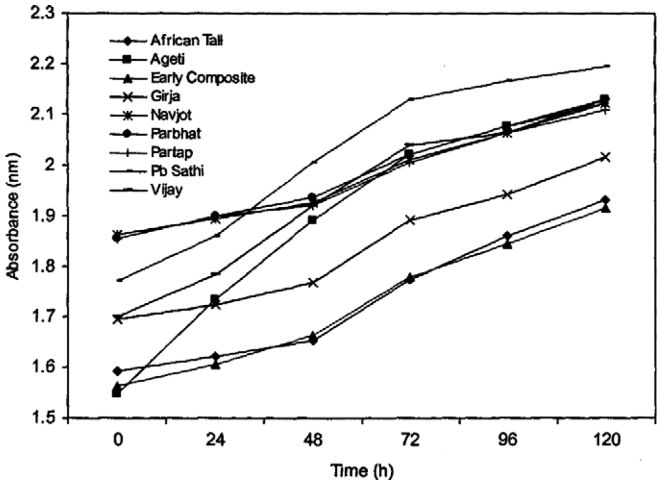

Fig. 1. Effect of storage duration on the turbidity of starch pastes from different corn varieties.

Fig. 1. Turbidity values of all starch suspensions increased progressively during storage of starch gels at 4 °C. Early Composite starch showed the lowest turbidity whereas Parbhat starch showed the highest. Turbidity development in starches during storage has been attributed to the interaction of several factors, such as granule swelling, granule remnants, leached amylose and amylopectin, amylose and amylopectin chain length, intra or interbonding, lipid and cross-linking substitution (Jacobson, Obanni, & BeMiller, 1997).

3.2. Gelatinization properties of starches

The gelatinization temperatures (onset, T_o; peak, T_p; and conclusion, T_c), enthalpy of gelatinization (ΔH_{gel}), peak height index (PHI) and gelatinization temperature range (R) for starches from different corn starches, measured using DSC are presented in Table 2. Significant difference was observed in T_o, T_p and T_c among starches from different corn varieties. The lowest T_o, T_p and T_c of 65.6, 69.9 and 75.1 °C, respectively, were observed for Girja starch, whereas Parbhat starch showed the highest value for the same (Fig. 2). These values are in agreement with those observed for normal corn starches (Ng, Duvick, & White, 1997; Seetharaman et al., 2001). The higher gelatinization temperatures for Parbhat starch indicated that more energy is required to initiate starch gelatinization. ΔH_{gel} for various corn starches ranged between 11.2 and 12.7 J/g (Table 2). Li, Berke, and Glover (1994) reported ΔH_{gel} in the range from 8.2 to 12.3 J/g for starches from tropical maize germplasm. The difference in ΔH_{gel} reflects melting of amylopectin crystallites. The variations in ΔH_{gel} could represent differences in bonding forces between the double helices that form the amylopectin crystallites, which, resulted in different alignment of hydrogen bonds within starch molecules (McPherson & Jane, 1999). PHI, a measure of uniformity in gelatinization, was found to be the lowest for Partap (2.34) starch, whereas it was found to be the highest for Pb Sathi (2.98). The R value was found

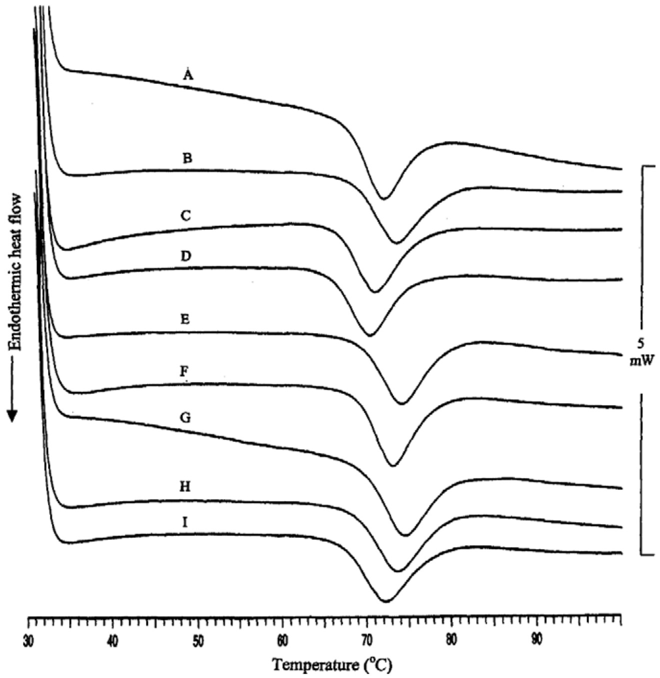

Fig. 2. DSC endotherms of gelatinization of starches from different corn varieties: (A) African Tall; (B) Ageti; (C) Early Composite; (D) Girja; (E) Navjot; (F) Partap; (G) Parbhat; (H) Pb Sathi; (I) Vijay.

Table 2
Gelatinization properties of starches from different corn varieties

Variety	T_o (°C)	T_p (°C)	T_c (°C)	ΔH_{gel} (J/g)	PHI	R
African Tall	67.5c	71.5b	76.5b	11.6ab	2.90b	8.0a
Ageti	68.3d	73.1cd	79.3d	12.2b	2.54ab	9.6b
Early Composite	66.3b	70.6a	75.9b	11.2a	2.60ab	8.6a
Girja	65.6a	69.9a	75.1a	11.3a	2.63ab	8.6a
Navjot	68.9e	73.8de	79.2d	12.4b	2.53ab	9.8b
Parbhat	69.0e	74.0e	79.7d	12.7c	2.54ab	10.0b
Partap	68.3d	73.3d	79.3d	11.7ab	2.34a	10.0b
Pb Sathi	68.6de	72.7c	77.8c	12.2b	2.98b	8.2a
Vijay	67.0c	71.9b	77.9c	11.7ab	2.39a	9.8b

T_o, onset temperature; T_p, peak temperature; T_c, conclusion temperature; ΔH_{gel}, enthalpy of gelatinization (dwb, based on starch weight); R, gelatinization range $2(T_p - T_o)$; PHI, peak height index $\Delta H_{gel}/(T_p - T_o)$.
Values with similar letters in the same column do not differ significantly ($p < 0.05$).

to be the lowest for African Tall and the highest for Parbhat and Partap starches. The high R values of Parbhat and Partap corn starches suggests the presence of crystallites of varying stability within the crystalline domains of its granule (Hoover, Li, Hynes, & Senanayake, 1997).

3.3. Retrogradation properties of starches

The molecular interactions (hydrogen bonding between starch chains) that occur after cooling of the gelatinized starch paste are known as retrogradation (Hoover, 2000). The retrogradation properties of various corn starches are presented in Table 3. Retrogradation (%) of starches from different corn varieties were ≈40–60% (Fig. 3). Yamin, Svendsen, and White (1997) reported retrogradation (%) values between 50% and 60%, for Oh 43 normal corn starches inbreds. Retrograded corn starches showed lower enthalpy than their native counterparts. This may be due to the weaker starch crystallinity of retrograded starch (Sasaki, Yasui, & Matsuki, 2000). ΔH_{ret} for corn starches ranged from 4.4 to 6.9 J/g, the lowest for Vijay and the highest for Ageti starch. ΔH_{ret} of 4.6–6.9 J/g has been reported in selected corn lines by Ji et al. (2003). The difference in ΔH_{ret} among various corn starches suggested differences in their tendency towards retrogradation. The transition temperatures of retrogradation were found to be lower than the gelatinization temperatures. This might be due to the fact that recrystallization of amylopectin branched chains occurred in a less ordered manner in stored gels, as it is present in native form. T_{o} for retrogradation ranged between 41.5 and 43.1 °C, the lowest for Ageti and the highest for Partap starch was observed. T_{o} values of retrogradation in the range between 42.9 and 48.1 °C for exotic corn inbred lines have been reported by Pollak and White (1997). Girja starch showed the lowest value for T_{p} of retrogradation whereas Partap had the highest value. The range for retrogradation temperature was found to be greater than the gelatinization temperature range. Similar observations have been reported earlier (Karim, Norziah, & Seow, 2000). African Tall and Early Composite starches showed the lowest R of retrogradation, whereas Partap and Ageti had the highest values.

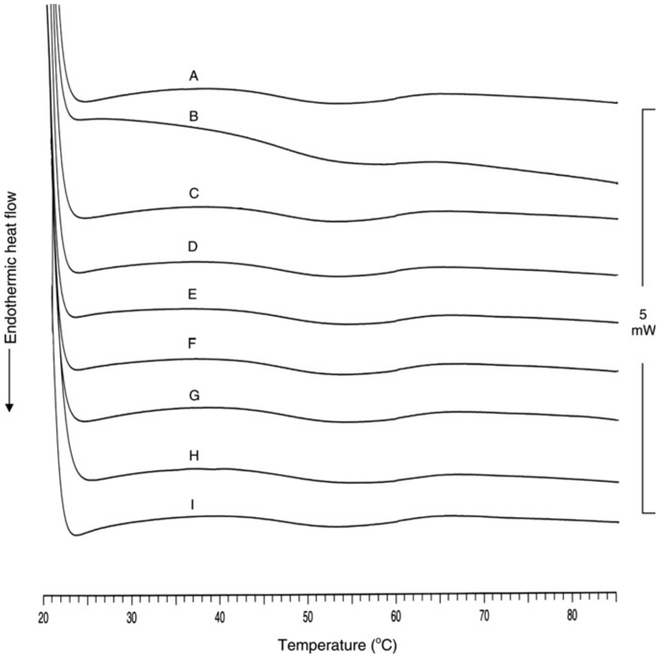

Fig. 3. DSC endotherms of retrogradation of starches from different corn varieties: (A) African Tall; (B) Ageti; (C) Early Composite; (D) Girja; (E) Navjot; (F) Partap; (G) Parbhat; (H) Pb Sathi; (I) Vijay.

3.4. Pasting properties of starches

Pasting properties of various corn starches have been summarized in Table 4. Significant difference in the pasting properties among different corn varieties was observed. All corn starches showed gradual increase in viscosity with increase in temperature (Fig. 4). The increase in viscosity with temperature may be attributed to the removal of water from the exuded amylose by the granules as they swell (Ghiasi, Varriano-Marston, & Hoseney, 1982). Peak viscosity (PV) for various corn starches ranged between 804 and 1252 cP, the lowest for Partap and the highest for African Tall and Early Composite starches. Ji et al. (2003) reported PV in the range between 152 and 222 RVU for selected corn lines. Trough viscosity (TV) was found to be the lowest for Pb Sathi (594 cP) and the highest for Parbhat (727 cP). Breakdown viscosity (BV) (measure of

Table 3
Retrogradation properties of starches from different corn varieties

Variety	T_{o} (°C)	T_{p} (°C)	T_{c} (°C)	ΔH_{ret} (J/g)	R	%R
African Tall	42.5b	52.4a	62.3ab	5.0ab	19.8a	43.1c
Ageti	41.5a	52.9ab	63.6bc	6.9c	22.8c	56.5e
Early Composite	42.7bc	52.6a	62.0a	4.9ab	19.8a	43.7c
Girja	42.4b	52.4a	62.1a	5.0ab	20.0a	44.2cd
Navjot	42.5b	53.6bc	63.1b	5.4b	22.2bc	43.5c
Parbhat	43.0c	53.6bc	63.4bc	5.2b	21.2b	40.9b
Partap	43.1c	54.5c	64.3c	4.9ab	22.8c	41.9bc
Pb Sathi	42.5b	53.3b	62.9b	5.7bc	21.6b	46.7d
Vijay	43.0c	53.1b	62.4ab	4.4a	20.2a	37.6a

T_{o}, onset temperature; T_{p}, peak temperature; T_{c}, conclusion temperature; ΔH_{ret}, enthalpy of retrogradation (dwb, based on starch weight); R, retrogradation range $2(T_{\text{p}} - T_{\text{o}})$; %$R$, ratio of enthalpy of retrogradation to enthalpy of gelatinization ×100.
Values with similar letters in the same column do not differ significantly ($p < 0.05$).

Table 4
Pasting properties of starches from different corn varieties

Variety	PV (cP)	TV (cP)	BV (cP)	FV (cP)	SV (cP)	P_{Temp} (°C)
African Tall	1252f	662bc	590f	1388e	726f	75.9a
Ageti	1000c	652b	348c	1222c	570c	77.4b
Early Composite	1250f	671c	579f	1321d	650de	75.9a
Girja	1196e	647b	549e	1324d	677e	77.4b
Nayjot	839b	697d	142b	877b	180b	80.6d
Parbhat	840b	727e	113a	868b	141a	83.8e
Partap	804a	676c	128ab	824a	148a	83.1e
Pb Sathi	1012c	594a	418d	1214c	629d	78.3c
Vijay	1063d	686cd	377c	1345de	659de	77.5b

PV, peak viscosity; TV, trough viscosity; BV, breakdown viscosity; FV, final viscosity; SV, setback viscosity; P_{Temp}, pasting temperature.
Values with similar letters in the same column do not differ significantly ($p < 0.05$).

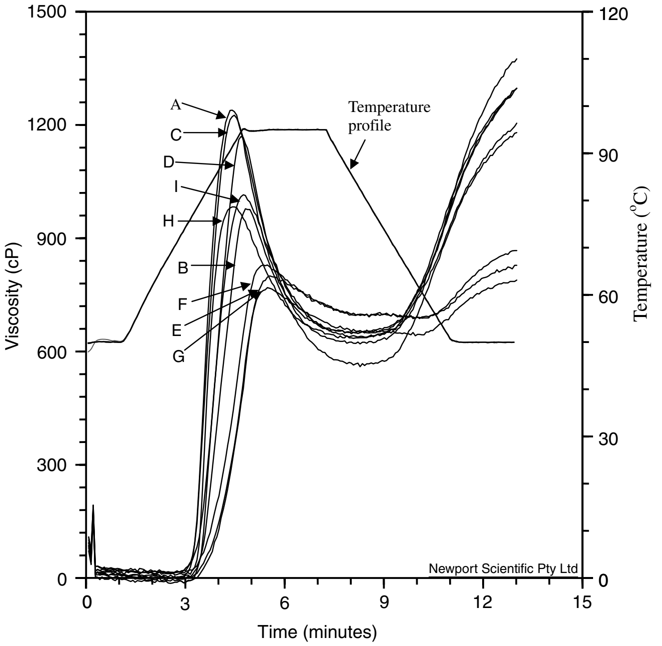

Fig. 4. Rapid visco analyzer pasting profiles of starches from different corn varieties: (A) African Tall; (B) Ageti; (C) Early Composite; (D) Girja; (E) Navjot; (F) Parbhat; (G) Partap; (H) Pb Sathi; (I) Vijay.

the cooked starch to disintegration) was found to be the lowest for Parbhat and the highest for African Tall starch. Final viscosity (FV) (indicates the ability of the starch to form a viscous paste) for different corn starches ranged from 824 to 1388 cP, the lowest shown by Partap and the highest by African Tall. Miles et al. (1985) reported that increase in final viscosity might be due to the aggregation of the amylose molecules. Setback viscosity (SV) (measure of synaeresis of starch upon cooling of the cooked starch pastes) for various corn starches differed significantly. Partap exhibited the lowest setback of 141 cP, whereas it was found to be the highest for African Tall (726 cP). The low PV, BV, FV and SV of Navjot, Parbhat and Partap starches correlate well with their low SP in water. Pasting properties are dependent on the rigidity of starch granules, which in turn affect the granule swelling potential (Sandhya Rani & Bhattacharaya, 1989) and amount of amylose leaching out in the solution (Morris, 1990). Pasting temperature (PT) (temperature at the onset of rise in viscosity) for various corn starches ranged between 75.9 and 83.8 °C, the lowest shown by African Tall and Early Composite and the highest by Parbhat starch. The high pasting temperature of Parbhat and Partap starch indicated their higher resistance towards swelling. Seetharaman et al. (2001) reported pasting temperatures in the range of 74.9–84.7 °C for Argentinian corn landraces.

3.5. Gel texture properties of starch gels

The textural properties of gels from different corn starches determined using the texture analyzer are shown in Table 5. The textural parameters of corn starch gels from different corn varieties varied significantly. Starch

Table 5
Textural properties of starch gels from different corn varieties

Variety	Hardness (g)	Cohesiveness	Gumminess	Springiness	Chewiness	Adhesiveness (gs)
African Tall	21.5a	0.418c	8.9a	0.805d	7.2b	38.6e
Ageti	28.0d	0.392b	10.9bc	0.623b	6.8ab	15.6a
Early Composite	26.0c	0.398bc	10.3b	0.590ab	6.1a	32.4d
Girja	24.1b	0.385	9.3	0.716c	6.6ab	20.6b
Navjot	27.5d	0.431d	11.8c	0.626b	7.4b	32.6d
Parbhat	31.1e	0.437d	13.6d	0.518a	7.0b	22.9c
Partap	32.3f	0.370a	11.9c	0.902e	10.8c	20.6b
Pb Sathi	27.5d	0.576e	15.8e	0.708c	11.2c	40.6f
Vijay	27.5d	0.434d	11.9c	0.614b	7.3b	40.3f

Values with similar letters in the same column do not differ significantly ($p < 0.05$).

gel from Partap showed the highest hardness (32.3 g), whereas African Tall starch gel showed the lowest (21.5 g). Seetharaman et al. (2001) reported the hardness of 13 selected Argentinian corn landraces in the range between 16.7 and 35 g. The gel firmness is mainly caused by retrogradation of starch gels, which is associated with the synaeresis of water and crystallization of amylopectin, leading to harder gels (Miles et al., 1985). Starches that exhibit harder gels tend to have higher amylose content and longer amylopectin chains (Mua & Jackson, 1997). Gumminess was found to be the highest for Pb Sathi (15.8) and the lowest for African Tall (8.9) starch gels. Chewiness was found to be the highest for Pb Sathi and the lowest for Early Composite starch gel. The mechanical properties of starch gels depend upon various factors, including the rheological characteristics of the amylose matrix, the volume fraction and the rigidity of the gelatinized starch granules, as well as the interactions between dispersed and continuous phases of the gel (Biliaderis, 1998). These factors are in turn dependent on the amylose content and the structure of the amylopectin (Yamin et al., 1999). The values for hardness, cohesiveness, springiness and adhesiveness of starch gels observed in the present study were comparable to those observed earlier for normal corn starches by Liu, Ramsden, and Corke (1999).

3.6. Pearson correlations among various properties of corn starches

Several significant correlations between the physicochemical, gelatinization, retrogradation, pasting and gel texture properties of the corn starches were observed (Table 6). SP was positively correlated to solubility ($r = 0.582$, $p < 0.05$). Interrelationships between the gelatinization parameters were observed. T_o was positively correlated to T_p and T_c ($r = 0.970$ and 0.890, respectively, $p < 0.01$). Ji et al. (2003) showed positive correlations between T_o and T_p for advanced generations of corn lines. ΔH_{gel} was observed to be positively correlated with T_o, T_p and T_c ($r = 0.900$, 0.902 and 0.828, respectively, $p < 0.01$). Singh, Kaur, Sandhu, Kaur, and Nishinari (2006) observed significant positive correlation between T_o, T_p and T_c with ΔH_{gel} for rice starches. PHI was negatively correlated to R ($r = -0.869$, $p < 0.01$). Relationship between the gelatinization and retrogradation properties was observed. ΔH_{gel} was positively correlated to the R of retrogradation. The thermal and pasting properties were observed to be related to each other. T_o, T_p and T_c of gelatinization were negatively correlated to PV ($r = -0.809$, -0.898 and -0.902, respectively, $p < 0.01$), BV ($r = -0.774$, -0.886 and -0.900, respectively, $p < 0.01$), FV ($r = -0.721$, -0.795 and -0.765, respectively, $p < 0.01$) and SV ($r = -0.686$, -0.779 and 0.762, respectively, $p < 0.01$) whereas they were positively correlated to PT ($r = 0.657$, 0.750 and 0.731, respectively, $p < 0.01$). ΔH_{gel} was negatively correlated to PV and BV ($r = -0.743$, -0.733, respectively, $p < 0.01$), FV and SV ($r = -0.623$ and -0.611, respectively,

Table 6
Pearson correlation coefficients between various properties of starches from different corn varieties

	AMY[a]	SP[a]	SOL[a]	T_o[a]	T_p[a]	T_c[a]	ΔH_{gel}[a]	PHI[a]	R[a]	$R(1)$[a]	PV[a]	BV[a]	FV[a]	SV[a]	PT[a]	HD[a]
SP[a]	−0.498															
SOL[a]	0.136	0.582[b]														
T_o[a]	0.519[b]	−0.742[c]	−0.227													
T_p[a]	0.560[b]	−0.827[c]	−0.258	0.970[c]												
T_c[a]	0.584[b]	−0.814[c]	−0.174	0.890[c]	0.968[c]											
ΔH_{gel}[a]	0.576[b]	−0.731[c]	−0.168	0.900[c]	0.902[c]	0.828[c]										
PHI[a]	−0.174	0.416	0.179	0.001	−0.236	−0.432	−0.023									
R[a]	0.444	−0.730[c]	−0.242	0.454	0.657[c]	0.788[c]	0.513[b]	−0.869[c]								
R(1)[a]	0.354	−0.717[c]	−0.179	0.720[c]	0.763[c]	0.805[c]	0.580[b]	−0.323	0.565[b]							
PV[a]	−0.506	0.956[c]	0.524[b]	−0.809[c]	−0.898[c]	−0.902[c]	−0.743[c]	0.475	−0.782[c]	−0.815[c]						
BV[a]	−0.457	0.933[c]	0.533[b]	−0.774[c]	−0.886[c]	−0.900	−0.733[c]	0.558	−0.846[c]	−0.745[c]	0.985[c]					
FV[a]	−0.210	0.859[c]	0.725[c]	−0.721[c]	−0.795[c]	−0.765[c]	−0.623[b]	0.426	−0.675[c]	−0.703[c]	0.925[c]	0.938[c]				
Sv[a]	−0.184	0.832[c]	0.706[c]	−0.686[c]	−0.779[c]	−0.762[c]	−0.611[b]	0.495	−0.727[c]	−0.645[c]	0.904[c]	0.940[c]	0.991[c]			
PT[a]	0.251	−0.914[c]	−0.781[c]	0.657[c]	0.750[c]	0.731[c]	0.620[b]	−0.464	0.714[c]	0.578[b]	−0.903[c]	−0.922[c]	0.945[c]	−0.943[c]		
HD[a]	0.511[b]	−0.811[c]	0.516[b]	0.590[b]	0.713[c]	0.787[c]	0.518[b]	−0.601[b]	0.781[c]	0.680[c]	−0.865[c]	−0.856[c]	−0.799[c]	−0.784[c]	0.838[c]	
GM[a]	0.792[c]	−0.623[b]	−0.302	0.663[c]	0.621[c]	0.542[b]	0.660[c]	0.137	0.222	0.396	−0.591	−0.505	−0.431	−0.360	0.490	0.609[b]

[a] AM, amylose content; SP, swelling power; SOL, solubility; T_o, onset temperature; T_p, peak temperature; T_c, conclusion temperature; ΔH_{gel}, enthalpy of gelatinization; PHI, peak height index; R, range of gelatinization; $R(1)$, range of retrogradation; PV, peak viscosity; BD, breakdown viscosity; FV, final viscosity; SB, setback viscosity; PT, pasting temperature; HD, hardness; GM, gumminess.

[b] Correlation is significant ($p < 0.05$).

[c] Correlation is significant ($p < 0.01$).

$p < 0.05$). Similar negative correlations between T_o, T_p, T_c and ΔH_{gel} with PV, BV and SV have been reported (Ji et al., 2003). SP was positively correlated with PV, BV, FV and SV ($r = 0.959$, 0.933, 0.859 and 0.832, respectively, $p < 0.01$) was observed. Similar positive correlation between SP and PV has been reported by Singh et al. (2006). Interrelationship between the various pasting parameters was observed. PT was negatively correlated to PV, BV, FV and SV ($r = -0.903$, -0.922, -0.945 and -0.943, respectively, $p < 0.01$). Singh et al. (2006) reported negative correlation of PT with PV, BV, FV and SV. PV was positively correlated to BV, FV and SV ($r = 0.985$, 0.925 and 0.904, respectively, $p < 0.01$). Ji et al. (2003) reported a positive correlation between PV and BV. Amylose was positively correlated to hardness ($r = 0.511$, $p < 0.05$) and gumminess ($r = 0.792$, $p < 0.01$) whereas SP was negatively correlated to these parameters. Similar positive correlation ($r = 0.70$) between amylose and hardness has been previously reported (Seetharaman et al., 2001). Hardness was positively correlated to T_p, T_c ($r = 0.713$ and 0.787, respectively, $p < 0.01$) and ΔH_{gel} ($r = 0.518$, $p < 0.05$) of gelatinization whereas it was negatively correlated to PV, FV and SV ($r = -0.865$, -0.799 and -0.784, respectively, $p < 0.01$). Similar positive correlation between T_p and hardness ($r = 0.24$, Singh, Johnson, White, Jane, & Pollak, 2001) and between ΔH_{gel} and hardness ($r = 0.44$, Ji et al., 2003) was observed for corn starches. Gumminess was positively correlated to hardness ($r = 0.609$, $p < 0.05$).

4. Conclusions

Variation in the physicochemical, gelatinization, retrogradation, pasting and gel texture properties of starches from different corn varieties was observed. African Tall and Early Composite showed higher swelling power, peak-, trough-, breakdown-, final- and setback viscosities and lower ΔH_{gel} and range of gelatinization. The correlation analysis of the physicochemical, thermal, pasting and gel textural properties of starches provided valuable information on the mechanisms contributing to the functional properties of the starches. Low amylose content of starch from African Tall resulted in lower hardness of its gel. T_o was negatively correlated to peak-, breakdown-, final- and setback viscosity and positively correlated to pasting temperature. ΔH_{gel} was negatively correlated to peak- and breakdown viscosity.

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