Characterization of Thermal Traits of Starches from Argentinian Maize Inbreds: Genotypic and Crop Year Variability

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ABSTRACT

Cereal Chem. 84(1):92–96

Thermal properties are among the most important end-use characteristics of starch from maize (*Zea mays* L.). Knowledge of the contribution of genotype and environment to the total variance for starch thermal properties is needed to aid in defining a testing strategy for selecting maize with desirable thermal starch properties. Thus, the objectives of this study were 1) to characterize the thermal properties of starches from a group of recently developed Argentine maize inbred lines, and 2) to assess the variability in starch properties attributable to genetic and crop year effects. Twelve inbred lines developed by the National Institute of Agricultural Technology (INTA) in Argentina derived from a wide array of germplasm sources were evaluated. Gelatinization and retrogradation properties were measured by differential scanning calorimetry. Enthalpy means for gelatinization were below means reported in the literature, suggesting possible energy savings when using these starches. The ratio between change in enthalpy for retrogradation and gelatinization was above the mean reported in the literature, suggesting a starch that may be useful as a dietary fiber. Significant environmental effects caused by crop year were detected. Some inbred lines, with smaller observed ranges and standard deviations across environments, may be more stable for some properties.

The starch industry continues to search for natural sources of starch with desirable functional properties to minimize the current practice of chemical modifications to achieve desired functions. The identification of sources of unique starch characteristics is an important objective because of the potential commercial benefits of these starches.

In the endosperm of cereals, starch occurs in the form of discrete granules of varying sizes. When starch granules are heated in the presence of water, the molecular order within the starch granules is disrupted. This process is called gelatinization. Studies have shown that gelatinization properties of starches are affected by factors including the size of the starch granule (Banks and Greenwood 1975), the degree of starch crystallinity (Zobel 1984), the amylose and amylopectin contents (Inouchi et al 1983), the fine structure of amylopectin (Shi and Seib 1995), and the presence of other components in starch such as phospholipids and phosphate esters (Jane et al 1996). In addition to the genetic background effect, gelatinization properties of starches can be altered by chemical modifications and heat treatments such as annealing.

Retrogradation is a process that occurs when the molecules of gelatinizated starch begin to reassociate, leading to a more ordered, somewhat crystalline, structure (Atwell et al 1988). The rate of retrogradation depends on several factors such as the molecular ratio of amylose to amylopectin, structures of the amylose and amylopectin molecules, holding temperature, starch concentration and concentrations of other ingredients such as surfactants and salts (Whistler and BeMiller 1997). The two major constituent polymers, amylose and amylopectin, have different effects on retrogradation of cooked starch.

Gelatinization and retrogradation properties of maize (*Zea mays* L.) starches were studied using differential scanning calorimetry (DSC). White et al (1990) demonstrated variability in thermal behavior among five open-pollinated populations of genetically variable maize, and significant differences among plants within the same population, indicating that genetic variability for thermal behavior of the starches, and likely for starch structure, may exist within populations. Additional research showed an environmental effect on DSC properties of starches from exotic maize populations grown in two environments (White et al 1991). Also, variations in DSC properties were reported for maize starches based on kernel maturity, that were likely due to fine structural differences during development (Ng et al 1997a).

Seetharaman et al (2001) characterized the thermal and functional properties of starch obtained from several Argentinian maize landraces and confirmed the existence of variability for these traits within and among landraces. Targeted values for starch traits desirable to the industry were reported for onset temperature of gelatinization as <61°C, for enthalpy of gelatinization of <9.5 J/g or > 14.5 J/g, for range of gelatinization of <5.5°C or >14.5°C, for enthalpy of retrogradation of < 3.8 J/g, and for percent retrogradation of < 20% or > 80% (Seetharaman et al 2001). Pollak and White (1997) found differences for thermal starch properties among lines from Argentina, South Africa, United States, and Uruguay. Recently, Scott and Duvick (2005) identified several quantitative trait loci (QTL) controlling starch thermal properties, although they explained a small amount of the genetic variability in two groups of recombinant inbred lines.

Further knowledge about physical starch properties of different genotypes is needed to develop hybrids more suitable for wet-milling end uses. Knowledge of the contribution of genotype and environment to the total variance for starch thermal properties, as well as of the stability of starch properties of different genotypes across environments (Ji et al 2004), is still needed to design reliable testing programs.

Since 2004, research in our Experiment Station has focused on evaluating maize genotypes for starches with unique functional properties. DSC parameters and values that are of particular interest for commercial applications of starch are gelatinization parameters for onset temperature, peak temperature, range of temperature, peak height index, and enthalpy; and retrogradation parameters for onset temperature, peak temperature, range of temperature, enthalpy, and percentage of retrogradation.

The objectives of this study were 1) to characterize the thermal properties of the starch from a group of recently developed Argentine maize inbred lines, and 2) to assess their variability attributable to genetic and environmental effects to define a testing strategy for selecting for thermal properties of starch. Inbred lines included in this study are considered a representative sample of the 43 lines obtained by the maize breeding program from the National Institute of Agricultural Technology (INTA) from 1992 to 2002.

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DOI: 10.1094/CCHEM-84-1-0092

MATERIALS AND METHODS

Plant Materials

A group of 12 inbred lines developed by INTA derived from a wide array of germplasm sources was used for this study (Table I). The lines are currently used as parents of experimental hybrids or planned crosses to develop new inbred lines. Lines LP453, LP124, LP199, and LP125r were obtained from broad genetic base populations after a minimum of seven generations of selfing. Lines LP168, LP1411, LP212, and LP236 derived from planned crosses; and LP299-2, LP223, LP662, and LP317 originated from hybrid cultivars after selfing. During their development, the lines were test-crossed to elite testers and selected for high combining ability for grain yield, low grain moisture, and standability. Lines included in this study were classified into three groups by visually observing kernel texture: flint (seven lines), semident (three lines), and semiflint (two lines), according to a scale slightly modified from that of Johnson and Russell (1982).

Seed samples of the lines were planted in the breeding nursery for seed increase during a maximum of five and a minimum of three cropping seasons. Seeds were collected by hand and dried at room temperature until reaching grain moisture equilibrium of ≈10%, the exact value for each sample depending on its kernel characteristics. Then seed samples were kept in cold storage (8°C) inside sealed plastic bags. Samples were identified by the inbred line name and the crop season of seed increase. Traits measured for each seed sample were starch thermal properties of gelatinization and retrogradation.

TABLE I
Maize Inbred Maize Lines, Codes, Genetic Origins, and Endosperm Texture

Line	Code	Origin	Kernel Texture
LP453	1	Composite Argentino-Caribe	Semident
LP168	2	(Line P465 × Exotic)F_2	Flint
LP317	3	Hybrid cultivars synthetic	Flint
LP212	4	(Flint cultivar × USDent line)F_2	Semiflint
LP236	5	(Flint cultivar × USDent line)F_2	Semiflint
LP125r	6	Synthetic Colorada Dura	Flint
LP124	7	Composite Colorado Precoz	Flint
LP662	8	Asgrow AX252 F_2	Flint
LP1411	9	(Line LP199 × line 3178)F_2	Flint
LP299-2	10	Pioneer hybrid cultivar synthetic	Semident
LP199	11	Composite II	Flint
LP223	12	Pioneer hybrid cultivar synthetic	Semident

Starch Extraction

Starch extractions of five kernels from each sample were accomplished using procedures previously developed by White et al (1990) and modified by Krieger et al (1997). The isolated starches contained <1.0% protein.

DSC Analysis

Thermal properties of samples were evaluated using differential scanning calorimetry (Pyris 6 DSC, equipped with PYRIS software for Windows XP package, v. 6.5.0.0088, 2003, Perkin-Elmer Instruments LLC, Norwalk, CT). Starch dry weight to water (1:2) aliquots were scanned for gelatinization from 30 to 120°C at 10°C/min and rescanned for retrogradation from 30 to 110°C at 10°C/min after storage at 4°C for 7 days as described by Ji et al (2004). All analyses were conducted in duplicate and the average values reported. Thermal starch properties considered in this study were onset temperature of gelatinization (T_{oG}), peak temperature of gelatinization (T_{pG}), range of temperature (R_G), change in enthalpy of gelatinization (ΔH_G), peak height index of gelatinization (PHI_G) defined as the relation ($2\Delta H_G/R_G$), onset temperature of retrogradation (T_{oR}), peak temperature of retrogradation (T_{pR}), range of temperature (R_R), change in enthalpy of retrogradation (ΔH_R), and percentage of retrogradation (P_R).

A typical DSC thermogram shows two endothermic peaks with increasing temperature. The first peak reflects the melting of amylopectin crystals, whereas the second peak reflects the melting of the amylose-lipid complex. In this study, the changes in the second peak were not reported because of the very small areas and poor baseline resolution, resulting in poor replicate values.

Statistical Methods

The obtained data set was unbalanced, thus, analyses of variance for all traits were performed using Proc GLM (SAS Institute, Cary, NC) following the model $y_{ij} = g_i + s_j + e_{ij}$, where y_{ij} are the observations for the *i*th line increased in the *j*th crop season, g_i and s_j denote the effect of the *i*th line and the *j*th crop season, respectively. The last term (e_{ij}) includes experimental error associated with y_{ij} observation plus the interaction effect between *i*th line and *j*th crop season, and its mean square was used as the denominator of *F*-tests. Laboratory determinations were performed in seed samples of different ages. Consequently, s_j also accounts for the confounded effect of the environmental conditions (climate and nutrition during seed development in the *j*th season) with the effect of time of seed storage. Sources of variation attributable to g_i and s_j are referred as to lines and environments, respectively. It was assumed that the environment during seed development had a

TABLE II
Least Squares Means of 12 Inbred Lines Cultivated in Different Crop Years for Starch Gelatinization and Retrogradation Thermal Properties[a]

Line	Code	T_{oG} (°C)	T_{pG} (°C)	R_G (°C)	ΔH_G (J/g)	PHI_G	T_{oR} (°C)	T_{pR} (°C)	R_R (°C)	ΔH_R (J/g)	P_R (%)
LP453	1	69.1	73.0	7.9	10.3	2.71	39.5	53.3	27.6	5.6	53.9
LP168	2	67.1	71.1	8.0	9.9	2.56	39.6	53.1	27.0	5.3	53.7
LP317	3	69.8	73.5	7.5	10.5	2.92	39.8	52.0	24.9	6.4	62.2
LP212	4	67.4	72.4	10.1	11.0	2.25	38.7	52.4	27.4	6.4	58.3
LP236	5	68.7	72.9	8.4	10.1	2.48	40.3	52.5	24.4	6.3	63.0
LP125r	6	68.1	72.3	8.4	10.0	2.48	39.7	52.2	24.9	5.9	59.2
LP124	7	68.4	72.2	7.6	10.3	2.85	38.6	51.8	26.4	6.0	58.1
LP662	8	68.4	72.6	8.4	10.0	2.40	41.7	53.4	23.4	6.8	68.3
LP1411	9	66.8	71.2	8.9	9.9	2.25	38.8	51.1	24.5	6.0	61.1
LP299-2	10	68.2	72.4	8.5	10.5	2.62	39.8	51.7	23.8	6.1	58.6
LP199	11	64.1	71.0	13.8	9.9	1.38	39.2	51.3	24.3	5.6	56.7
LP223	12	69.1	73.2	8.2	10.9	2.74	39.9	52.7	25.6	6.8	62.0
Maximum		69.8	73.5	13.8	11.0	2.92	41.7	53.4	27.6	6.8	68.3
Minimum		64.1	71.0	7.5	9.9	1.38	38.6	51.1	24.3	5.3	53.7

[a] Gelatinization thermal properties: T_{oG}, onset temperature; T_{pG}, peak temperature; R_G, range of temperature; PHI_G, peak height index; ΔH_G, change in enthalpy. Retrogradation thermal properties: T_{oR}, onset temperature; T_{pR}, peak temperature; R_R, range of temperature; ΔH_R, change in enthalpy; P_R, percent of retrogradation.

TABLE III
Least Squares Means of Five Crop Years Across 12 Inbred Lines for Starch Gelatinization and Retrogradation Thermal Properties[a]

Crop Year	Code	T_{oG} (°C)	T_{pG} (°C)	R_G (°C)	ΔH_G (J/g)	PHI$_G$	T_{oR} (°C)	T_{pR} (°C)	R_R (°C)	ΔH_R (J/g)	P_R (%)
1999	1	68.2	72.2	8.1	9.7	2.47	40.4	51.9	23.0	6.4	66.2
2000	2	68.2	72.4	8.4	9.7	2.39	39.3	52.0	25.3	5.8	59.9
2001	3	68.6	72.6	7.9	10.2	2.71	38.8	52.5	27.6	6.0	58.2
2002	4	67.0	72.6	11.3	10.0	1.87	40.0	53.1	26.1	5.5	54.9
2003	5	67.7	71.9	8.4	11.7	2.92	39.7	52.1	24.8	6.9	58.7

[a] Gelatinization thermal properties: T_{oG}, onset temperature; T_{pG}, peak temperature; R_G, range of temperature; PHI$_G$, peak height index; ΔH_G, change in enthalpy. Retrogradation thermal properties: T_{oR}, onset temperature; T_{pR}, peak temperature; R_R, range of temperature; ΔH_R, change in enthalpy; P_R, percent of retrogradation.

TABLE IV
Analysis of Variance for Starch Gelatinization and Retrogradation Thermal Properties of a Group of 12 Inbred Lines Cultivated in Different Crop Seasons[a]

Source of Variation	DF	T_{oG} (°C)	T_{pG} (°C)	R_G (°C)	ΔH_G (J/g)	PHI$_G$	T_{oR} (°C)	T_{pR} (°C)	R_R (°C)	ΔH_R (J/g)	P_R (%)
Model	15	***	***	***	***	***	ns	ns	*	***	*
Lines	11	***	***	***	ns	***	ns	ns	ns	*	ns
Flint vs. Soft	1	***	***	ns	**	ns	ns	ns	ns	ns	ns
Semident vs. semiflint	1	**	ns	**	ns	**	ns	ns	ns	ns	ns
Environments	4	***	*	***	***	***	ns	ns	**	***	**
Error	41										
Mean		68.2	72.3	8.3	10.5	2.6	39.6	52.3	25.3	6.3	59.8
CV (%)		1.3	0.9	12.0	6.9	13.6	4.2	2.7	11.4	11.2	11.5

[a] Gelatinization thermal properties: T_{oG}, onset temperature; T_{pG}, peak temperature; R_G, range of temperature; PHI$_G$, peak height index; ΔH_G, change in enthalpy. Retrogradation thermal properties: T_{oR}, onset temperature; T_{pR}, peak temperature; R_R, range of temperature; ΔH_R, change in enthalpy; P_R, percent of retrogradation. DF, degrees of freedom; CV, coefficient of variation.

stronger effect over the starch properties than the elapsed time of storage. Line source of variation was split into two 1 DF orthogonal contrasts: hard (flint) versus soft (semident and semiflint) inbred lines, and semident versus semiflint inbred lines. *F*-tests for declaring significance of sources of variations were made considering Type III sum of squares. Differences among least squares means were tested following Tukey-Kramer (Kramer 1956). Inbred lines were considered as the classifying variable, with intraclass correlation coefficients (Steel and Torrie 1980) for thermal properties of starch computed using Proc GLM (SAS). Thus, the greater the intraclass correlation coefficient, the greater the magnitude of the variability associated with genotype in comparison with the total variability, which included both genotype and environment.

RESULTS AND DISCUSSION

The ranges of least squares mean values for starch gelatinization parameters were 64.1°C (LP199) to 69.8°C (LP317) for T_{oG}, 71.0°C (LP199) to 73.5°C (LP317) for T_{pG}, 7.5°C (LP317) to 13.8°C (LP199) for R_G, 9.9 J/g (LP168, LP199, LP1411) to 11.0 J/g (LP212) for ΔH_G, and 1.38 (LP199) to 2.92 (LP317) for PHI$_G$ (Table II). The complete set of lines presented least squares mean values within the target values sought by the industry (Seetharaman et al 2001). For starch retrogradation parameters, the ranges of least squares mean values for lines were 38.6°C (LP124) to 41.7°C (LP662) for T_{oR}, 51.1°C (LP1411) to 53.4°C (LP662) for T_{pR}, 23.4°C (LP662) to 27.6°C (LP453) for R_R, 5.3 J/g (LP168) to 6.8 J/g (LP223, LP662) for ΔH_R, and 53.7% (LP168) to 68.3% (LP662) for P_R.

Compared with the mean values obtained by Pollak and White (1997) from other inbred lines, Argentinian lines included in this study had smaller R_G, ΔH_G, T_{oR}, greater T_{oG}, PHI$_G$, R_R, P_R, and similar ΔH_R. Knutson et al (1982), studying high-amylose inbred lines, attributed differences in R_G and ΔH_G between lines to differences in starch granule size. Regarding starch gelatinization, ranges of least squares means for environment were 67.0°C (2002) to 68.6°C (2001) for T_{oG}, 71.9°C (2003) to 72.6°C (2001, 2002) for T_{pG}, 7.9°C (2001) to 11.3°C (2002) for R_G, 9.7 J/g (1999, 2000) to 11.7 J/g (2003) for ΔH_G, and 1.87 (2002) to 2.92 (2003) for PHI$_G$. For starch retrogradation traits, ranges of least squares means for environment were 38.8°C (2001) to 40.4°C (1999) for T_{oR}, 51.9°C (1999) to 53.1°C (2002) for T_{pR}, 23.0°C (1999) to 27.6°C (2001) for R_R, 5.5 J/g (2002) to 6.9 J/g (2003) for ΔH_R, and 54.9% (2002) to 66.2% (1999) for P_R (Table III). Significant differences among lines were found for T_{oG}, T_{pG}, R_G, PHI$_G$ ($P < 0.01$), and ΔH_R ($P < 0.1$) (Table IV).

Significant differences occurred between hard (flint) and soft (semident and semiflint) lines for T_{oG}, T_{pG} ($P < 0.01$) and ΔH_G ($P < 0.05$). Significant differences were found between semiflint and semident lines for T_{oG}, R_G, and PHI$_G$ ($P < 0.05$). Nevertheless, because of the small number of lines included in each texture class, results are not indicative of any relationship between kernel texture and thermal properties, beyond the group of lines included in this study. Differences among lines grouped according to their kernel texture were declared not significant for all starch retrogradation traits.

For T_{oG}, significant differences ($P < 0.10$) among lines (data not shown) involved those with $T_{oG} \geq 69.1$°C (LP223, LP317, LP453) and those with $T_{oG} \leq 67.1$°C (LP199, LP1411, LP168). For T_{pG}, significant differences ($P < 0.10$) among lines involved those with $T_{pG} \geq 72.6$°C (LP223, LP662, LP236, LP317, LP453) and those with $T_{pG} \leq 71.2$°C (LP199, LP1411, LP168). For PHI$_G$, significant differences ($P < 0.10$) among lines involved those with PHI$_G \geq 2.25$ (LP453, LP168, LP317, LP235, LP125r, LP124, LP662, LP299-2, and LP223) and the lowest (1.38) PHI$_G$ line (LP199). For R_G, significant differences ($P < 0.10$) among lines involved those with $R_G \geq 10.1$°C (LP212, LP199) and those with $R_G \leq 8.2$°C (LP168, LP317, LP124, LP223). For ΔH_R, significant differences ($P < 0.10$) were detected between LP223 (6.8) and LP168 (5.3). The ratio $\Delta H_R/\Delta H_G$ (0.6) was greater than that (0.5) found by Wang et al (1992).

Significant differences caused by environment were detected for T_{oG}, R_G, ΔH_G, PHI$_G$, ΔH_R ($P < 0.01$), R_R, P_R ($P < 0.05$), and T_{pG} ($P < 0.1$). Ng et al (1997b) indicated that many environmental factors such as temperature regime during kernel development, soil type, sowing date, location, and year affect thermal properties.

TABLE V
Observed Means, Ranges, and Standard Deviations of 12 Inbred Lines Cultivated in Different Crop Seasons for Starch Gelatinization Thermal Properties

		Means					Range					Standard Deviation				
Crop Year	Code	T_{oG} (°C)	T_{pG} (°C)	R_G (°C)	ΔH_G (J/g)	PHI_G	T_{oG} (°C)	T_{pG} (°C)	R_G (°C)	ΔH_G (J/g)	PHI_G	T_{oG} (°C)	T_{pG} (°C)	R_G (°C)	ΔH_G (J/g)	PHI_G
LP453	1	69.3	73.0	7.3	10.4	2.86	2.5	1.8	1.4	1.8	0.80	1.1	0.8	0.6	0.7	0.39
LP168	2	67.2	70.9	7.4	10.3	2.78	2.8	2.7	0.8	2.4	0.52	1.1	1.0	0.3	0.9	0.22
LP317	3	70.0	73.4	6.9	10.5	3.07	0.4	0.4	1.3	3.4	0.72	0.2	0.2	0.5	1.4	0.32
LP212	4	67.3	72.4	10.1	11.4	2.34	2.4	2.2	5.7	3.1	1.65	1.2	0.9	2.3	1.3	0.63
LP236	5	68.7	72.8	8.3	10.3	2.56	2.2	1.6	3.9	3.2	1.87	0.9	0.6	1.4	1.2	0.67
LP125r	6	68.2	72.1	7.8	10.3	2.69	2.0	1.0	2.9	3.3	1.24	0.8	0.4	1.2	1.5	0.47
LP124	7	68.6	72.1	7.0	10.7	3.06	1.8	1.9	1.2	2.9	1.12	0.8	0.8	0.5	1.1	0.46
LP662	8	68.4	72.6	8.4	10.0	2.40	2.5	1.2	2.5	3.1	0.58	1.0	0.5	1.1	1.2	0.24
LP1411	9	66.7	71.3	9.1	10.1	2.25	1.6	1.7	3.9	3.1	1.16	0.8	0.7	1.7	1.5	0.49
LP299-2	10	68.1	72.3	8.4	10.7	2.70	3.2	1.7	6.5	2.8	1.80	1.1	0.7	2.5	1.1	0.62
LP199	11	64.6	71.2	13.1	9.6	1.46	0.4	0.0	0.7	0.3	0.11	0.3	0.0	0.5	0.2	0.08
LP223	12	69.1	73.1	8.1	11.2	2.82	3.7	2.6	2.6	2.7	1.59	1.3	1.0	1.1	1.1	0.54

[a] Gelatinization thermal properties: T_{oG}, onset temperature; T_{pG}, peak temperature; R_G, range of temperature; PHI_G, peak height index; ΔH_G, change in enthalpy.

TABLE VI
Observed Means, Ranges, and Standard Deviations of 12 Inbred Lines Cultivated in Different Crop Seasons for Starch Retrogradation Thermal Properties[a]

		Means					Range					Standard Deviation				
Crop Year	Code	T_{oR} (°C)	T_{pR} (°C)	R_R (°C)	ΔH_R (J/g)	P_R	T_{oR} (°C)	T_{pR} (°C)	R_R (°C)	ΔH_R (J/g)	P_R	T_{oR} (°C)	T_{pR} (°C)	R_R (°C)	ΔH_R (J/g)	P_R
LP453	1	39.4	53.1	27.4	5.7	55.0	5.7	5.8	8.6	1.5	4.8	2.8	2.4	4.2	0.6	2.1
LP168	2	39.5	52.9	26.7	5.6	54.5	2.9	4.3	12.2	2.6	22.7	1.1	1.9	4.6	1.1	8.5
LP317	3	39.7	52.0	24.7	6.6	63.4	2.6	2.2	5.4	1.9	20.9	1.2	0.9	2.3	0.8	8.8
LP212	4	38.6	52.4	27.7	6.5	56.8	2.6	3.1	7.4	2.9	16.4	1.1	1.2	3.4	1.0	6.4
LP236	5	40.3	52.5	24.3	6.4	62.8	5.9	3.8	10.7	2.0	21.7	2.1	1.5	3.7	0.8	8.4
LP125r	6	39.7	52.0	24.7	6.2	59.9	2.3	2.9	10.0	1.6	5.7	1.0	1.2	3.8	0.8	2.2
LP124	7	38.6	51.6	26.1	6.2	58.8	2.0	2.9	6.9	1.1	5.4	0.9	1.1	3.0	0.5	2.1
LP662	8	41.7	53.4	23.4	6.8	68.3	7.2	3.7	9.2	2.2	26.9	3.0	1.7	3.8	1.0	12.4
LP1411	9	38.6	51.2	25.1	5.9	59.5	2.3	1.1	4.4	1.3	17.2	1.1	0.5	1.9	0.6	8.5
LP299-2	10	39.8	51.7	23.7	6.3	58.4	3.3	1.7	7.2	2.1	13.4	1.3	0.7	2.4	0.8	4.8
LP199	11	38.8	51.2	24.9	5.7	56.0	2.4	1.4	2.7	1.4	4.5	1.4	0.7	1.4	0.7	2.3
LP223	12	39.9	52.6	25.5	6.9	61.8	4.2	4.3	1.3	3.2	24.2	1.5	1.5	0.5	1.1	9.5

[a] Retrogradation thermal properties: T_{oR}, onset temperature; T_{pR}, peak temperature; R_R, range of temperature; ΔH_R, change in enthalpy; P_R, percent of retrogradation.

Considering the range and standard deviations for the observed values for starch gelatinization traits (Table V), lines LP199, LP317, and LP168 exhibited the least variation across environments, whereas lines LP299-2 and LP212 exhibited greater dispersion of observations than any other line included in this study. For starch retrogradation traits, lines LP199 and LP124 had lower ranges and standard deviations than other lines (Table VI). In contrast, lines LP453, LP168, LP662, and LP223 showed more variation across environments. Thus, LP199, LP317, and LP168 were the most stable inbred lines for gelatinization, and LP199 and LP124 were the most stable for retrogradation.

Intraclass correlation coefficients were 0.61 (T_{oG} and T_{pG}), 0.40 (R_G), 0.15 (ΔH_G), 0.29 (PHI_G), 0.01 (T_{oR}, T_{pR}), 0.00 (R_R), 0.11 (ΔH_R), and 0.10 (P_R). The relative magnitude of genotypic and environmental variabilities, as indicated by the intraclass correlation coefficients, revealed that the environmental effects were more important for retrogradation starch traits than for gelatinization starch traits. Low genetic variability and great contribution of environmental effects would limit improvement of retrogradation traits by selection, at least in the germplasm analyzed.

CONCLUSIONS

Most of the tested inbred lines presented PHI_G means useful for the industry. Starch from these lines would have high thickening power of >14.5 J/g in a narrow range of temperature of <5.5°C. The ΔH_G found in these lines were below means reported in the literature for other genotypes. Thus starches from these sources should be more energy efficient during gelatinization. The P_R was ≈0.6, above the mean reported in the literature. Significant environmental effects caused by crop year were detected, as reported earlier by other authors (White et al 1991; Ji et al 2004). Some inbred lines seemed to be more stable for some thermal starch properties in terms of their smaller observed range and standard deviations across environments. According to the statistical model, the effect of genotype × environment interaction was included within the error term. Results suggest that characterization of lines in terms of their genetic stability for thermal starch properties deserves further analysis using approaches that consider genotype × environment interaction parameters.

ACKNOWLEDGMENTS

We gratefully acknowledge the technical assistance of Silvina Yanigro in the sample starch extractions and DSC operation.

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[Received June 5, 2006. Accepted October 7, 2006.]