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Identifying and using value-added traits in GEM accessions (Latin American maize) to improve Corn-Belt dent corn

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Identifying and using value-added traits in GEM accessions (Latin American maize) to improve Corn-Belt dent corn

by

Suvrat Kumar Singh

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

Major: Food Science and Technology
Major Professor: Lawrence A. Johnson

Iowa State University
Ames, Iowa
2000

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DEDICATION

I would like to dedicate my dissertation to my mother who died of cancer in India while I was a student in the United States.

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A number of close friends and colleagues have assisted the author at various stages of the work reported in this thesis. It is a mater of pleasure and honor for the author to thank all of them sincerely. Among them are Mr. S. Fox, Mr. S. Grund, Mr. S. Moizuddin, Ms. Eleen, and Dr. J. Strohl. The author wishes to place special acknowledgment and thanks for the tremendous patience, love, and support given by his wife, Rekha Singh, and children, Rohan and Robin.

INTRODUCTION AND LITERATURE REVIEW

Dissertation Organization

This dissertation contains a general introduction, including an overview of wet-milling procedures, and an introduction to the compositional, physical, and wet-milling properties of corn and functional properties of cornstarch. The dissertation also includes a general discussion of heterosis and heterotic pattern useful to breeders in the corn seed industry for capturing value-added traits that are identified in selected GEM accessions. The general introduction is followed by five research papers and a general conclusion. One paper, "Comparison of laboratory and pilot-plant corn wet-milling procedures" has already been published in the journal *Cereal Chemistry* (74:40-48). The other four will be submitted to *Cereal Chemistry* shortly.

Wet-milling Procedures

Annual corn production in the United States now exceeds 236 million tons (nearly 10 billion bushels). The corn wet-milling industry is the second largest market for corn, accounting for 16% of the production in 1992 (Corn Annual 1993). Corn wet milling involves chemical and mechanical processes in which starch, gluten, germ, and fiber fractions, the four major fractions of corn, are separated into as pure forms as possible. The process involves softening of the kernel in steepwater, followed by grinding operations. Fractions are separated by taking advantage of differences in physical properties (e.g., density and particle size) of the fractions. Reliable wet-milling methods are needed for laboratory and pilot-plant evaluations of process variations and new genetically modified hybrids.

The first attempts to simulate wet milling in the laboratory were by Zipf et al (1950) and Watson et al (1951). Zipf et al (1950) used a one-step SO_2 steeping system, whereas Watson et al (1951) used a two-step steeping procedure increasing the lactic acid concentration and decreasing the SO_2 concentration during the course. Watson et al (1951) also developed a static but countercurrent steeping procedure. Steinke et al (1991) used countercurrent steeping with recycling to closely simulate commercial practice. The more closely industrial steeping practices were simulated, the more representative the yields were of industrial results. Some procedures have used a Quaker City (plate) Mill (Eckhoff et al 1993, 1996), and others used food blenders (Fox et al 1992, Steinke and Johnson 1991, Steinke et al 1991) to grind the corn, but the method and equipment used in grinding seemed to have little effect on results. Either centrifugation (Fox et al 1992, Steinke and Johnson 1991, Steinke et al 1991) or starch tabling (Zipf 1950, Watson et al 1951, Eckhoff et al 1993, 1996) has been used for starch/gluten separation. Most researchers believe starch tabling gives more reproducible results. Some have used multiple tabling or tabling in combination with starch filtration (Dimler et al 1944, Zipf 1950, Watson et al 1951, Anderson 1963); but, most have used one-step tabling (Eckhoff et al 1993, 1996). Not all investigators have used the same table length, pitch, and flow rate, which affect separation efficiency. The fiber fraction has often been separated and washed differently. The best results have been achieved when fiber was separated into two fractions, coarse and fine fiber, and when the fiber was extensively washed. Most of these methods use 1 Kg of corn.

Recently, Eckhoff et al (1996) developed a relatively simple method of wet milling 100 g of corn useful for screening large numbers of samples for wet-milling properties. The procedure has proven to be a practical method for breeders to assess large numbers of corn for wet-milling potential. The method involved grinding 100 g of steeped corn in a food blender with blunted blades to release the germs followed by washing the germ and coarse fiber together on a 7-mesh screen. The flow through the screen was finely ground in a Quaker City Mill. The finely ground slurry was washed on a 200-mesh screen to remove the fine fiber. After adjusting the specific gravity of the through-flow to 1.04, the millstarch was pumped onto a 2.6-m (8-ft) long table with a pitch of 0.0104 (cm/cm) for starch/gluten separation. Gluten cake was obtained by vacuum filtration.

Slotter and Longford (1944) developed a pilot-plant procedure to wet mill corn and wheat. About 25 Kg of corn was steeped for 46 hr at 52°C. The steeped grain was ground in a 16-inch (41-cm) Buhrstone Mill with distilled water. The germ was removed by flotation. The degermed slurry was screened on a 26-mesh screen and then over No. 17 standard bolting cloth in a Rotex screener. The fraction retained on the screen was washed with water. The millstarch was allowed to flow down a 14-m long table for starch/gluten separation (tabling). Starch recoveries were 87.2% for corn. The protein content of the corn gluten fraction was much lower than that of commercially prepared gluten.

Anderson (1957) discussed in detail a pilot-plant wet-milling procedure. Batches of corn (100 Kg) were steeped in stainless-steel tanks. The steeped corn was ground in a 8-

inch (20-cm) Buhrstone Mill to release germ. The germ fraction was recovered by screening on a sieve shaker equipped with a 26-mesh screen. The through-flow from the germ-separator was dewatered on a Rotex shaker equipped with a 200-mesh screen, and passed through either a Buhrstone Mill or a Reitz Disintegrator for fine grinding. Coarse and fine fiber fractions were washed and collected on 20- and 200-mesh screens, respectively. Both tabling and centrifugation methods were used for starch/gluten separation.

Rubens (1990) also described a pilot-plant corn wet-milling facility based on Anderson's (1957) design. A continuous batch-type steeping procedure was used to steep 3 bu corn. Germ was recovered with a hydroclone (germclone). The overflow (germ) was discharged into a sieve shaker equipped with 30-mesh screen. The underflow was recycled until the sample was relatively free of germ. Fine fiber was removed by using a sieve shaker equipped with 230-mesh screen. Final starch/gluten separation involved thickening of the millstarch with a disc-nozzle centrifuge. Primary gluten separation also involved disc-nozzle centrifugation, and final washing and protein reduction steps were accomplished by using multiple-staged hydroclones.

Latin America as a Source of Germplasm

Several researchers have expressed their concerns about the narrowing of the genetic base of maize (National Academy of Science 1972, Brown 1975, Crossa and Gardner 1987). Their main concerns were about increased genetic vulnerability to changes in environmental factors and pest resistance. Utilization of exotic germplasm for improving maize has been suggested (Hallauer 1978, Geadlemann 1984). This may not only protect the crop from unforeseen agronomic problems, but also may add value to the corn in terms of processing and starch properties.

Corn hybrids with improved wet-milling properties and unique starch characteristics have been of major interest of seed companies, wet millers, and end users of starch. Researchers have successfully developed high-yielding hybrids with higher percentages of starch, protein, or oil in the kernel, but little has been done to improve the millability of corn, proximate compositions of milled fractions, and the physical properties of corn, which would be of specific interest to the wet millers and grain processors.

Corn hybrids have been developed in the past by using adapted germplasm, but seldom have elite inbreds been crossed with exotic germplasm to develop new breeding lines. The U.S. Germplasm Enhancement Project (GEM) is a unique cooperation of public and private sectors, which has initiated research effort to strengthen U.S. corn hybrids in terms of increased yields and value-added traits. GEM is the next stage of Latin American Maize Project (LAMP) which was launched by U.S. Department of Agriculture, Agriculture Research Services (USDA/ARS) in 1987. The principle goal of GEM is to utilize and maintain the irreplaceable maize germplasm bank of 12 Latin American countries.

LAMP has evaluated 12,000 accessions at 70 locations in the United States and Latin America. Screening of these accessions was done on the basis of yield potential and agronomic characteristics. Two hundred sixty-eight of these accessions were selected as potential source of high yields, then fifty-one chosen to initiate GEM.

Functional Properties of Starch

Starch is the second most abundantly available carbohydrate on earth, second to cellulose. Starch is an important component of foods; not only as a source of energy, but also as a texture builder in food. Starch interacts with water in ways important to functionality in food. Water-holding properties of starch change upon heating, which results in altered thermal, pasting, and gelling properties of starch. These properties can be measured by differential scanning calorimetry (DSC), rapid visco analyzer (RVA), and texture analyzers (Instron or Voland Texture analyzer). Based on their thermal, pasting, and gelling properties, starch is used in food systems to impart different functions.

Some of the more important thermal properties for the food industry are gelatinization temperature (Tp), enthalpy change of gelatinization (ΔH), and percent retrogradation (%Retro). In general, for many food applications, one looks for lower values these properties because they result in easy cooking, greater shelf-life, and improved refrigerated storage stability.

One major function of starch, especially in convenience food, is to impart thickening or viscosity to the food material. Some of the important physical properties of starch are peak viscosity (Vp), cold paste viscosity (CPV), breakdown (BD), and setback (SB) as they indicate thickening potential and viscosity stability.

Starch in its native state is insoluble in water due to hydrogen bonds stabilizing the granular structure. Upon heating starch in aqueous media, the heat overcomes the energy to break the hydrogen bonds and as a result the granules swell. With a continuous supply of heat, the granules rupture, and the amylose fraction of the granules is released into solution. Dispersed amylose, amylopectin, and granule fragments entangle with each other and viscosity develops.

Native starch has limited functional uses in convenience food. Starch is often chemically modified by using Federally approved chemicals to impart desired functionality. The process of chemical modification of starch is expensive and often not desired by consumers and environmentalists. In recent years, starch chemists and food technologists have initiated searches for native starches, which possess the functionality of a modified starch and new and unique functionality. The search for such native starches has been done by screening corn varieties on the basis of their thermal, pasting, and gelling properties, and enhancing the properties of interest by breeding techniques.

Much work has already shown that thermal properties of maize-starch varies considerably (Li et al 1994, Campbell et al 1995a, and Pollak and White 1997). However, except for starch mutant lines, most of the natural variation, while statistically significant, has not been practically significant to end-users. Attempts have been made to identify and enhance useful thermal properties of starch by selfing natural variants (Wang et al 1992, Wang et al 1993, Campbell et al 1994, 1995b).

Heterosis

Heterosis or hybrid vigor is defined as the superiority of the progeny over the parental mean or over the parent with the highest expression of the trait (Robinson and Moll 1965). Crosses made among different lines provide information on heterosis, which can be used to develop or modify hybrids with desired traits. Mostly, the term heterosis is used for improvement in yield in corn or other crops. Based on heterosis, parents from exotic and elite inbred lines can be selected and used to increase yield potential.

Heterosis can be described as "mid-parent" heterosis or "high-parent" heterosis. Mid-parent heterosis is the percentage deviation of the progeny from the mean of the parents. High-parent heterosis is the percentage deviation of the progeny from the high parent.

Hallauer and Miranda (1988) defined exotic as "all the germplasm that does not have immediate usefulness without selection for adaptation for a given area." Further, they explained that useful genes from exotic germplasm would not be available until they are incorporated in the adapted germplasm. Wellhausen (1965) emphasized that enhanced heterosis and genetic diversity could be achieved in U.S. Corn-Belt lines by using exotic germplasm.

Duvick (1981) stated "We do not need diversity of deleterious genes; we do need to learn how to identify useful gene combinations in exotic materials, and how to transfer them efficiently and quickly." Once accessions with useful genes are identified, they can be used to produce lines for hybrid breeding programs.

Utilization of exotic germplasm could produce hybrids with unique traits favorable for improved wet-millability and novelty starches. Researchers have already successfully developed high-yielding hybrids with higher percentages of starch or oil in the kernel.

Until recent years, the breeders have been involved in using the valuable genetic variations almost solely for improving yield potential and pest resistance. Now, with advancements in technology and methodology for determining the impact of varietal differences on the end uses of grain, breeders can tailor corn genetics for new hybrids for specific end uses, such as corn hybrids with improved wet-milling properties and unique starch characteristics which are of major interest of seed companies, wet millers, and end users of starch.

Thesis Objectives

The objectives of this thesis were to:

- Identify and/or develop suitable procedures for assessing wet-milling characteristics of corn and for recovering samples of starch to assess functional properties.
- Assess 49 selected GEM accessions for their compositional, physical, and wet-milling properties.
- Determine the impact on compositional, physical, and wet-milling properties of crossing selected GEM accessions with two common Corn-Belt inbreds (B73 and Mo17).
- Assess the starches recovered from the same 49 selected GEM accessions for their thermal, pasting, and gelling properties.
- Determine the impact on thermal, pasting and gelling properties of crossing selected GEM accessions with the two common Corn-Belt inbreds.

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COMPARISON OF LABORATORY AND PILOT-PLANT CORN WET-MILLING PROCEDURES[1]

A paper submitted to Cereal Chemistry

S.K. Singh[2], L.A. Johnson[3], L.M. Pollak[4], S.R. Fox[5], and T.B. Bailey[6]

ABSTRACT

One waxy and three regular yellow dent corn hybrids were wet milled by using two scales of laboratory (modified 100-g and 1-Kg) procedures and a pilot-plant (10-kg) procedure. The modified 100-g and 1-Kg laboratory procedures gave similar yields of wet-milling fractions. Starch yields and recoveries were significantly lower for the pilot-plant

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[5] Laboratory Research Technician III, Center for Crops Utilization Research, Iowa State University, Ames, IA 50011.

[6] Professor, Department of Statistics, Iowa State University, Ames, IA 50011.

procedure, whereas gluten and fiber yields were greater because of their high contents of unrecovered starch. Protein contents of the starches obtained by all three procedures were within commercially acceptable limits (<0.5% db for normal dent corn and <0.30% for waxy corn). Rankings for starch yields and starch recoveries for the four hybrids, having very different physical and compositional properties, were the same for all three procedures. The harder the grain, the lower the yield and recovery of starch. Least significant differences ($P < 0.05$) for starch yield were 0.8% for the modified 100-g procedure, 1.2% for the 1-Kg procedure, and 2.0% for the pilot-plant procedure.

INTRODUCTION

In 1995, the United States produced over 7.4 billion bushels of corn, of which an estimated 19% or 1.4 billion bushels was wet milled during the 1995-96 crop year (Economic Research Service, 1996). Corn wet milling involves chemical, biochemical, and mechanical operations to separate corn into relatively pure fractions of starch, gluten, germ, and fiber. The process involves softening the kernel in steepwater, followed by grinding operations. Fractions are separated by taking advantage of differences in the physical properties (density and particle size) of the fractions. Reliable wet-milling methods are needed for laboratory and pilot-plant evaluations of process variations and new genetically modified hybrids.

The first attempts to simulate wet milling in the laboratory were by Zipf et al (1950) and Watson et al (1951). Zipf et al (1950) used a one-step SO_2 steeping system, whereas Watson et al (1951) used a two-step steeping procedure increasing the lactic acid concentration and decreasing the SO_2 concentration during the course of steeping. Watson et al (1955) also described a static but countercurrent steeping procedure. Steinke et al (1991) used countercurrent steeping with recycling to closely simulate commercial practice. The more closely industrial steeping practices were simulated, the more representative the yields for mill fractions were of industrial results. Some procedures have used a Quaker City Mill (plate-type) for endosperm disruption (Watson 1951, Eckhoff et al 1993, 1996), and others used only food blenders (Fox et al 1992, Steinke and Johnson 1991, Steinke et al 1991) to grind the corn. The method and equipment used in grinding seemed to have little effect on results.

Either centrifugation (Fox et al 1992, Steinke and Johnson 1991, Steinke et al 1991) or starch tabling (Zipf 1950, Watson et al 1951, Eckhoff et al 1993, 1996) has been used for starch-gluten separation. Most researchers believe starch tabling gives more reproducible results. Some have used multiple tabling or tabling in combination with starch filtration (Dimler et al 1944, Zipf 1950, Watson et al 1951, Anderson 1963); but, most have used one-step tabling (Eckhoff et al 1993, 1996). Not all investigators have used the same table length, pitch, and millstarch flow rate. The fiber fraction has often been separated and washed by different methods. The best results have been achieved when fiber was separated into two fractions, coarse and fine fiber, and when the fiber was extensively washed. Most of these methods have used 1 Kg of corn.

Recently, Eckhoff et al (1996) developed a relatively simple method of wet milling 100 g of corn for screening large numbers of samples for wet-milling properties. The procedure has proven to be quite useful to breeders. The method involved grinding 100 g of steeped corn in a food blender with blunted blades to release germ followed by washing the germ and coarse fiber together on a 7-mesh screen. The flow through the screen was finely ground in a Quaker City mill. The finely ground slurry was washed on a 200-mesh screen. After adjusting the specific gravity of the throughflow to 1.04, the millstarch was pumped onto a 2.6-m (8-ft) long table with a pitch of 0.0104 (cm/cm) for starch/gluten separation. Gluten cake was obtained by vacuum filtration.

Slotter and Longford (1944) developed a pilot-plant procedure to wet mill corn and wheat. About 25 Kg of corn were steeped for 46 hr at 52°C. The steeped grain was ground in a 16-in. (41-cm) Buhrstone Mill with distilled water. The germ was removed by flotation. The degermed slurry was screened on a 26-mesh screen and then over No. 17 standard bolting cloth in a Rotex screener. The fraction retained on the screen was washed with water. The millstarch was allowed to flow down a 14-m long table for starch-gluten separation. Starch recoveries were 87.2% for corn. The protein content of the corn gluten fraction was much lower than that of commercially prepared gluten.

Anderson (1957) discussed, in detail, a pilot-plant wet-milling procedure. Batches of corn (100 Kg) were steeped in stainless-steel tanks. The steeped corn was ground in a 8-in. (20-cm) Buhrstone Mill to release germ. The germ fraction was recovered by screening on a sieve shaker equipped with a 26-mesh screen. The throughflow from the germ-separator was dewatered on a Rotex shaker equipped with a 200-mesh screen, and passed through either a Buhrstone mill or a Reitz disintegrator for fine grinding. Coarse and fine fiber fractions were washed and collected on 20- and 200-mesh screens, respectively. Both tabling and centrifugation methods were used for starch-gluten separation.

Rubens (1990) also described a pilot-plant corn wet-milling facility procedure designed to more closely simulate commercial wet milling than an easier design by

Anderson (1957). A continuous batch-type steeping procedure was used to steep 3 bu corn. Germ was recovered with a hydroclone (germclone). The overflow (germ) was discharged into a sieve shaker equipped with 30-mesh screen. The underflow was recycled until the sample was relatively free of germ. Fine fiber was removed by using a sieve shaker equipped with 230-mesh screen. Final starch-gluten separation involved thickening of the millstarch with a disc-nozzle centrifuge. Primary gluten separation also involved disc-nozzle centrifugation, and final washing and protein reduction steps were accomplished by using multiple-staged hydroclones.

The objectives of the present work were to determine whether wet-milling results vary with scale and to determine how great differences must be for significance in each procedure.

MATERIALS AND METHODS

Sample Preparation

Three commercial yellow dent corn hybrids, Pioneer 3245, 3317, and 3394 (Pioneer Hi-bred International, Inc., Savoy, IL), and a commercial waxy corn (Custom Farm Seed, Momence, IL) were acquired. The corn was cleaned by using a Carter-Dayco dockage tester equipped with a 6.35-mm round-hole sieve. Additional foreign material and broken kernels were removed by hand. Triplicate sample sets for each scale of wet milling (100 g, 1 Kg, and 10 Kg) were prepared for each hybrid, placed into polyethylene bags, and stored at 4°C until used.

Compositional and Physical Properties

Moisture contents of the corn were determined by using AACC method 44-15A (AACC 1983). Starch, protein, and crude free fat contents (dry basis) of each hybrid were estimated in triplicate by using an Infratec Grain Analyzer, a near-infrared transmittance (NIR-T) analyzer (Tecator, Hoganas, Sweden).

Kernel absolute density was determined by using an AccuPyc 1330 pycnometer (Micrometrics, Norcross, GA). Test weight was determined by using Federal Grain Inspection Services (FGIS 1988) standard methods. Thousand-kernel weight was determined by using an electronic counter (Syntron, Homer City, PA). Kernel hardness was determined with the Stenvert hardness tester by measuring the height of a 20-g sample ground through a 2-mm screen of a MicroHammer Mill IV (Glen Mills Inc., Maywood, NJ). Values were determined in triplicate and adjusted to a 15% moisture basis by using moisture adjustment equations reported by Dorsey-Redding et al (1990).

Wet Milling

Corn was wet milled in triplicate for each of three procedures: modified 100-g laboratory (Fig. 1), 1-Kg laboratory (Fig. 2), and 10-Kg pilot-plant (Fig. 3). The 1-Kg laboratory and the 10-Kg pilot-plant procedures were developed at Iowa State University, whereas the modified 100-g laboratory procedure was a modification of the 100-g wet-milling procedure developed by Eckhoff et al (1996).

Modified 100-g Procedure

The 100-g procedure, originally developed by Eckhoff et al (1996), was modified for improved germ plus coarse fiber separation, fine grinding, fine fiber separation, and starch-gluten separation. A single-stage steeping process was used to steep 100 g of corn in 200 mL of steep solution containing 0.2% SO_2 and 0.5% lactic acid. Static steeping was carried out for 48 hr at 50°C. The steeped corn was ground in a 1-L Waring Blendor (Waring Product Division, New Hartford, CT) for 4 min at 60% speed. The blades of the blender were replaced with round-edged, dull blades made from 2-mm thick aluminum plate.

The ground slurry was transferred to a 7-mesh screen fitted over the top of a 3.5-L Waring Blendor. Germ and coarse fiber retained on the screen were dispersed and squeezed with a rubber spatula. The screen, along with germ and coarse fiber, was transferred to a special 10-L plastic bucket (Tucker Housewares, Leominster, MA). The bucket was then placed in a sieve shaker (CCS Scientific, Fairfax, VA) for 5 min. The germ and coarse fiber on the screen were occasionally dispersed with a spatula.

The flow through the screen was transferred to the 3.5-L Waring Blendor for fine grinding. Surfaces of the screen and bucket were washed into the 3.5-L Waring Blendor with 250 mL of distilled water. The screen containing germ and coarse fiber was placed on a 20-cm diameter pie tray and dried in a forced-air oven at 50°C for 24 hr. The remaining slurry was then ground in the 3.5-L Waring Blendor at full speed for 2 min. The grinder was stopped for 5 sec after 30-sec intervals to achieve better grinding.

Approximately 1 L of excess water was decanted from the finely ground slurry. The slurry was transferred to a 200-mesh screen fitted over the 8-L bucket. Decanted water was used to wash the slurry with continuous dispersing using a spatula. The slurry was then washed with 600 mL of distilled water.

Starch-gluten separation, gluten filtration, and germ separation were done by using the Eckhoff et al (1996) procedure with only slight modification. The last 15 cm of protein-rich starch on the table was scraped into the gluten slurry. Starch was allowed to dry on the starch table for 24 hr at room temperature. Gluten was dried in a forced-air oven at 50°C for 24 hr.

1-Kg Procedure

The 1-Kg laboratory procedure, developed at Iowa State University is similar to methods employed by Steinke and Johnson (1991), but incorporates several improvements. Corn (1 Kg) was steeped at 50°C using a two-step, static, batch steeping procedure: (1) steeping for 36 hr with a 2-L solution containing 0.05% SO_2 and 1.5% lactic acid and then (2) steeping for an additional 12 hr with a 2-L solution of 0.1% SO_2 and 0.5% lactic acid. The steeped corn was ground with an equal weight of water in a 1-L Waring Blendor for 2 min at one-third speed. The blades were not altered from what was provided by the manufacturer.

To facilitate germ floatation, 1 L of distilled water was added. Germs were hand skimmed by using a strainer and were washed on a 60-mesh screen with 500 mL of water. The degermed slurry was ground in a 1-L Waring Blendor at full speed for 2 min with blades as were provided. The finely ground slurry was screened for 5 min through a series of 100- and 200-mesh sieves by using a Ro-tap sieve shaker (W.S. Tyler, Cleveland, OH). Coarse and fine fiber fractions retained on the 100- and 200-mesh screens, respectively, were washed twice by using 2 L of distilled water for each screen.

The combined through-flow was allowed to settle for 16 hr, and then the specific gravity was adjusted to 1.04 by decanting excess water. The millstarch was pumped with a peristaltic pump at the rate of 300 mL/min onto a starch table (6.1 m x 10.16 cm) with 0.60° pitch. The decant water was pumped onto the table, at the same rate, immediately following the millstarch to wash the starch. After 10 min of settling, 3.5 L of distilled water was pumped onto the table to rinse the starch. An additional 500 mL of distilled water in a squeeze bottle was also used to wash the surface of the starch. The starch was allowed to dry on the table at room temperature for 24 hr. The last 30 cm (at the distal end of the table), being rich in gluten, was scraped off the table as an inseparable fraction. The remaining 5.8 m was scraped off as starch. The gluten was centrifuged for 20 min at 5,860 x g to remove water.

10-Kg Pilot-Plant Procedure

A single-step static steeping process was used to steep 10 Kg of corn in a 265-L (70-gal) capacity, steam-jacketed, stainless-steel tank (Viatec, Belding, MI). The 50-L steeping solution contained 0.2% SO_2 and 0.5% lactic acid. The steeped corn was ground in a 12-in. (30-cm) Bauer Mill (model 12 disc mill, Andritz Sprout-Bauer Inc., Muncy, PA). The grinding and feeder speeds were 900 and 400 rpm, respectively. A continuous stream of water was supplied to the grinder at the rate of 5 L/min along with the corn. The total grinding time was 5 min. At the end of grinding, about 5 L of additional water was used to wash the grinder.

To facilitate germ flotation, the specific gravity of the ground corn slurry was adjusted to 1.05 by adding about 15 L of water. Germ was then hand-skimmed by using a strainer and washed with 5 L of water on a 60-mesh screen. The wash water was added to the ground slurry. The degermed slurry was ground twice at 3,200 rpm by using a 0.5 mm, and then a 0.05-mm reduction size cutter plate in a Stephan Mikrocut grinder (model MC10, Stephan Machinery Corp., Columbus, OH). An additional 5 L of distilled water was used to rinse the grinder. The finely ground slurry was continuously screened through a 50-mesh screen with a 30-in. (75-cm) Vibro Screen sieve shaker (model K 30-1-SS, Kason Corporation, Linden, NJ). Coarse fiber retained on the screen was recycled and washed twice on the 50-mesh screen spraying 30 L (2 x 15-L) of distilled water at the rate of 5 L/min. The flow through the 50-mesh screen was passed to a 200-mesh screen for fine-fiber screening. The fine fiber retained on the 200-mesh screen was recycled and washed twice through the 200-mesh screen by spraying 20 L (2 x 10 L) of distilled water at the rate of 5 L/min.

The flow through the 200-mesh screen, dilute millstarch, was collected in a plastic drum and allowed to settle at 4°C for 16 hr. The specific gravity of the millstarch was adjusted to 1.04 by decanting excess water. The millstarch was pumped at the rate of 1.5 L/min onto a starch table (6.1 m x 50.8 cm) at 0.60° pitch. A plastic drum was placed at the distal end of the table to collect the gluten and water fractions. Decant water (to prevent loss of starch) was pumped onto the table, at the same rate, immediately following the millstarch. Tabled starch was rested (allowed to stand) for 10 min, 30 L of distilled water was pumped onto the table to rinse the starch. An additional 5 L of distilled water in a squeeze bottle was used to rinse the surface of the starch. The starch was allowed to dry on the table at room temperature for 24 hr with a fan blowing air over it from the pumping end. The last 30 cm (at the distal end of the table), being rich in gluten, was scraped off the table as an inseparable fraction. The remaining 5.8 m was scraped off as starch.

Proximate Analysis of Wet-Milled Products

Protein contents were determined for all fractions of the 1-Kg and the pilot-plant procedure. Protein contents were determined in duplicate according to the Corn Refiners' Association macro-Kjeldahl method A-18 (CRA 1986). Because of the limited amounts of fractions available in the modified 100-g procedure, only the starch and gluten fractions were analyzed for protein content. Crude free fat contents were determined according to AOAC method 14-084 and 14-085 (AOAC1984) for the starch, gluten, fiber, germ, and inseparables fractions obtained by the 1-Kg laboratory procedure and the 10-Kg pilot-plant procedure. Crude free fat content of the gluten fraction for the pilot-plant procedure was not determined because this fraction was not dried. Moisture contents were determined according to AOAC method 14.004 (AOAC 1984).

Statistical Analysis

An unpaired, parametric, multiple comparison test (SAS 1984) was used to compare means and to determine least significant differences (LSD) at $P < 0.05$. Simple t-tests were used when comparing two means.

RESULTS AND DISCUSSION

Proximate and Physical Properties

The hybrids used in this study were selected on the basis of having expected large differences in wet-milling properties as well as considerable variation in compositional and physical properties. For instance, Pioneer 3394 is relatively soft and known for its good wet-milling characteristics; Pioneer 3245 is moderately hard and was not expected to have excellent wet-milling characteristics; Pioneer 3317 is relatively soft and was expected to have good wet-milling characteristics; and waxy hybrids are notorious for their poor wet-milling properties (Reubens 1990).

The four hybrids varied considerably in grain physical properties and protein content; other proximate components did not vary greatly (Table I). The ranges for starch and protein contents were from 71.8 to 72.4% and from 9.3 to 10.8%, respectively. Absolute density (LSD = 0.01%) and kernel hardness (LSD = 0.15 cm), which are prime factors in predicting millability of corn (Zehr et al 1995, Fox et al 1992), ranged from 1.25 to 1.31 g/cm^3 and from 9.34 to 10.1 cm, respectively. Test weight (LSD = 0.8 lb/bu) and thousand-kernel weight (LSD = 10.7 g) ranged from 54.8 to 59.5 lb/bu and from 266 to 378 g, respectively. These wide ranges were needed to provide a sample set suitable for this type of study.

Yields of Solid Wet-Milling Fractions

The differences in yields of wet-milled solid fractions among the hybrids were greater than differences between procedures (Table II). Pioneer 3317 produced the greatest starch yield, followed by Pioneer 3394 and 3245 and the waxy hybrid. Differences in starch yields among hybrids were significant. Starch yields were more reproducible in the modified 100-g procedure (LSD = 0.8%), followed by the 1-kg procedure (LSD = 1.2%) and then the pilot-plant procedure (LSD = 2.0%).

The modified 100-g and 1-Kg procedures gave similar starch yields for all four hybrids, but the pilot-plant procedure produced significantly lower yields. Rankings based on starch yields of the four hybrids were the same for all three procedures.

Standard deviations and the LSD for starch yield in the modified 100-g procedure were modestly lower than those of the 100-g procedure developed by Eckhoff et al (1996) (LSD = 0.8 vs 1.0%), but our yields were much more reproducible than the values reported by Zehr et al (1996) for the unmodified 100-g procedure (LSD = 0.8 vs 2.8%). The standard deviation of the starch yield for the 1-Kg procedure was similar to those of other laboratory wet-milling procedures (Anderson 1963, Steinke and Johnson 1991, Steinke et al 1991, Fox et al 1992, Eckhoff et al 1993, Singh and Eckhoff 1995).

The pilot-plant procedure produced higher gluten yields than did the modified 100-g and the 1-Kg procedure. Reproducibility in gluten yield was highest for the modified 100-g procedure (LSD = 0.8%) followed by the 1-Kg procedure (LSD = 1.2%) and then the pilot-plant procedure (LSD = 1.5%).

Standard deviations in gluten yields for the modified 100-g procedure were similar to those of the 100-g procedure developed by Eckhoff et al (1996), but yields were more reproducible than values (LSD = 0.8 vs 2.1%) reported by Zehr et al (1996). The standard deviations for gluten yields in the 1-Kg procedure were similar to that of the laboratory wet-milling procedure (Eckhoff et al 1993) despite different methods being used for gluten separation. Fox et al (1992) used centrifugation, whereas Eckhoff et al (1993) used vacuum filtration for gluten separation.

Germ yields were lower in the modified 100-g procedure than in the 1-Kg and pilot-plant procedures, except for the waxy corn for which the modified 100-g procedure gave the greatest germ yield. Germ separation for the modified 100-g procedure was done differently than in the 1-Kg and pilot-plant procedures. The germ separation step for the modified 100-g procedure was very sensitive to the absolute density of corn. Corn with low absolute density results in large numbers of broken germs, which cannot be recovered by this procedure.

Standard deviations of germ yield for the modified 100-g procedure were similar to that of the 100-g procedure (Eckhoff et al 1996), but yields were more reproducible than the values (LSD = 0.6 vs 1.6%) reported by Zehr et al (1996). Standard deviations of germ yields for the 1-Kg procedure were similar to those of the laboratory wet-milling procedure (Eckhoff et al 1993).

Higher fiber yields reflected incomplete fiber washing and greater amounts of residual starch in the fiber. Consequently, this resulted in lower starch yields. Lower fiber yields were obtained in the modified 100-g procedure because the amount of process water used per gram of corn was much greater (20:1) than for the other two procedures. Fiber yields in the pilot-plant procedure were higher than for the 1-Kg procedure despite a greater ratio for the pilot-plant procedure (13:1) than for the 1-Kg procedure (11:1). Rubens (1992) also reported high fiber yields for his pilot-plant procedure.

Inseparable solids for the pilot-plant procedure were significantly greater than for the 1-Kg procedure. Most other wet-milling procedures do not separate an inseparable fraction; however, we often find it helpful to do so when differentiating milling characteristics because differences are often quite apparant when examining this fraction.

Starch Recoveries

Differences in starch recovery among all hybrids were significant when using the modified 100-g procedure, but Pioneer 3317 and 3394 gave similar yields when using the 1-Kg and pilot-plant procedures (Table III). The modified 100-g procedure had the highest reproducibility (LSD = 1.00%) followed by the 1-Kg procedure (LSD = 1.60%) and then the pilot-plant procedure (LSD = 3.73%).

The greatest starch recovery was achieved when using the modified 100-g procedure followed by the 1-Kg procedure and then the pilot-plant procedure. Starch recoveries for the modified 100-g and 1-Kg procedures were similar, but both were significantly different from the pilot-plant procedure. The rankings of the four hybrids, however, were the same for all three procedures.

Most researchers have reported starch yields as measures of millability of corn. Few researchers have used starch recovery, the ratio of starch yield to available starch determined by NIR-T, for comparison. Starch recoveries in the modified 100-g procedure were similar to values reported by Zehr (1995) (Table III). Starch recoveries were greater for the 1-Kg procedure than values reported by Anderson (1963). For the pilot-plant procedure, starch recoveries were comparable with those of the pilot-plant procedure reported by Rubens (1990), despite different techniques being used for starch-gluten separation.

Yields of Liquid Wet-Milling Fractions

The four hybrids produced significantly different light-steep-liquor solids in the modified 100-g and 1-Kg procedures, but the pilot-plant procedure did not detect any differences among hybrids (Table IV). The 1-Kg and pilot-plant procedures produced similar light-steep-liquor solids, despite different steeping protocols. Both procedures differed significantly from the modified 100-g procedure for all hybrids except for the waxy corn, for which the three procedures produced significantly different light-steep-liquor solids. The difference between the modified 100-g and pilot-plant procedures for light-steep-liquor solids could be attributed to the different weight ratios of total steepwater to corn for steeping: 2:1 for the modified 100-g procedure and 5:1 for the pilot-plant procedure.

The amount of light-steep-liquor solids derived from the modified 100-g procedure was comparable to that from other procedures (Anderson 1963, Rubens 1990, Eckhoff et al 1993, Singh et al 1995, Eckhoff et al 1996, Shandera et al 1995, Zehr et al 1996). Yields of light-steep-liquor solids in the 1-Kg and pilot-plant procedures were similar to that of Fox et al (1992), but were much greater than the values reported by other researchers.

Gluten filtration for the modified 100-g and 1-Kg procedures was done using different techniques, which probably accounts for the difference in filtrate solids yields. This fraction was not produced in the pilot-plant procedure because we did not have, at the time, pilot-plant gluten dewatering equipment.

The four hybrids produced significantly different total soluble solids for the 1-Kg procedure, but the modified 100-g procedure could not detect hybrid differences. The 1-Kg procedure gave significantly greater total dissolved solids than did the modified 100-g procedure. Yields of total dissolved solids for the modified 100-g procedure were similar to other procedures (Watson 1951, 1986; Anderson 1963, Reubens 1990, Eckhoff and Tso 1991, Steinke and Johnson 1991). Total dissolved solid yields for the 1-Kg procedure were less than the values reported by Fox et al (1992), for a two-step steeping procedure.

Protein Contents of Wet-Milling Fractions

Purities of the wet-milling fractions are important factors to be considered in assessing the millabilities of corn. Although the wet-milling industry targets about 0.3% protein in starch, 0.5% protein is generally accepted. The industry standard for gluten protein content is 60%(at 11%moisture), but lab-scale wet-milling procedures typically approach only 50% protein.

Mean protein contents in starch for the four hybrids and three procedures were within the acceptable limits (Table V). Highest reproducibilities were achieved in the pilot-plant procedure (LSD = 0.02%) followed by the 1-Kg procedure (LSD = 0.05%) and then the modified 100-g procedure (LSD = 0.07%). Waxy corn gave the least amount of protein in starch for the three procedures. Our pilot-plant procedure produced starch with less protein than the procedure developed by Rubens (1992).

Variation of protein content in gluten was greatest in the pilot-plant procedure (LSD = 6.6%), followed by the modified 100-g procedure (LSD = 4.7%) and then the 1-Kg procedure (LSD = 3.4%). Protein contents of gluten were similar for the modified 100-g and the 1-Kg procedure for the four hybrids and were similar to other laboratory procedures (Watson et al 1951, Anderson 1963, Steinke and Johnson 1991, Fox et al 1992). Our pilot-plant procedure produced gluten with significantly lower amounts of protein than were achieved in the laboratory. Lower starch yields, but higher gluten yields, for the pilot-plant procedure indicated that a considerable amount of starch was transported into the gluten fraction, which decreased the protein content in the gluten. The poor millability of the waxy corn was also observed by Rubens (1992).

Protein contents of germ, fiber, and inseparables were similar for the 1-Kg and pilot-plant procedures, except for Pioneer 3317, for which protein contents of fiber for the 1-Kg and pilot-plant procedures were significantly different. LSDs for protein contents of the germ and fiber fractions among hybrids were smaller for the 1-Kg procedure than for the pilot-plant procedure.

Protein contents of light-steep-liquor solids for the 1-Kg procedure were significantly greater than for the pilot-plant procedure for Pioneer 3245 and 3317, but for Pioneer 3394 and waxy, both yielded similar protein content in the fraction. Variations in protein contents in light-steep-liquor solids were greater for the 1-Kg procedure (LSD = 3.5%) than for the pilot-plant procedure (LSD = 2.7%).

Protein contents of filtrate solids were similar for all four hybrids, except for Pioneer 3317, which was significantly greater than the others. No protein was observed in the rinse water of any hybrid.

Crude Free Fat Contents of Wet-Milling Fractions

Crude free fat contents for the 1-Kg and pilot-plant procedures were generally similar for all fractions (Table VI). The greatest crude free fat content of germ was observed for Pioneer 3245, which had highest oil content in the kernel as determined by NIR-T. Crude free fat contents were similar to values reported by Watson et al (1951) and Fox et al (1992).

CONCLUSIONS

The modified 100-g and 1-Kg procedures produced similar starch and gluten yields and also values similar those reported by industry. Our pilot-plant procedure produced lower starch and greater gluten yields, which we attributed to difficulty in achieving complete starch separation from fiber and gluten. Protein contents of the starch and gluten in all three procedures were similar to other laboratory procedures. Waxy corn produced lower starch yields, but greater gluten yields, with lower protein contents in starch. The protein contents of the starch produced by all three procedures were within acceptable limits (<0.50% for normal dent corn and <0.30% for waxy corn). Rankings of the four hybrids based on starch yields and starch recovery were the same for all three procedures.

Some starch ended up in the fiber fraction when using the pilot-plant procedure because of incomplete washing. The protein contents of fiber for the 1-Kg procedure were less than for the pilot-plant procedure; thus, more water should be used to wash fiber in the pilot-plant procedure. Germ separations for the 1-Kg and the pilot-plant procedure were similar, but the modified 100-g procedure was less reproducible.

The significantly greater speed (4-5 samples per day sustainable rateper person) and the excellent reproducibility make the 100-g procedure very useful in screening large numbers of corn samples for wet-milling properties, for which there is considerable recent interest. However, the amount of fractions recovered often limit usefulness (e.g., testing functional properties of starch). The 1-Kg procedure achieves modest speed (one sample per day sustainable rate per person), good reproducibility, and sufficient quantities of fractions for screening most functional properties. Although our pilot-plant procedure produced lower starch and higher gluten and fiber yields, and with less reproducibility and with considerable investment of time (two to threes days per sample sustainable rate with two persons) than the other procedures, it is useful, in some instances, to determine differences in millabilities of hybrids, but more importantly to obtain large amounts of representative materials from genetically modified hybrids for applications development. This study also verifies our previous observations (Fox et al 1992) that different corn hybrids have different wet-milling characteristics; that these differences can be shown by different scales of milling trials; and that the wet-milling industry may benefit economically from selecting hybrids with improved properties.

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TABLE I
Compositional and Physical Properties of Wet-Milled Corn

Property	Hybrids				
	Pioneer 3245	Pioneer 3317	Pioneer 3394	Waxy	LSD[a]
Compositional[b]					
Starch (%)	72.0a ± 0.05	72.4b ± 0.42	71.9a ± 0.08	71.8a ± 0.1	0.4
Protein (%)	10.8c ± 0.60	9.4a ± 0.10	9.9b ± 0.15	9.3c ± 0.11	0.2
Crude free fat (%)	3.86a ± 0.18	3.75a ± 0.12	3.74a ± 0.12	3.65a ± 0.01	0.29
Physical[c]					
Absolute density (g/cc)	1.29b ± 0.00	1.25a ± 0.00	1.29b ± 0.00	1.31c ± 0.00	0.01
Test weight (lb/bu)	58.9b ± 0.07	54.8a ± 0.25	58.4b ± 0.78	59.9c ± 0.10	0.8
1000-kernel weight (g)	266.2a ± 6.6	272.3a ± 6.2	334.8b ± 5.1	378.4c ± 4.6	10.7
Kernel hardness (cm)	9.50b ± 0.06	10.10d ± 0.12	9.93c ± 0.06	9.34a ± 0.06	0.15

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[a] Least significant difference. Values in the same row with different letters (a-d) are significantly different ($P < 0.05$).

[b] Reported on a dry basis. Means of three observations ± one standard deviation.

[c] Reported on a 15% moisture basis. Means of three observations ± one standard deviation.

Table II
Yields (% db) of Solid Wet-Milling Fractions[a]

Fraction/Procedure	Hybrids Pioneer 3245	 Pioneer 3317	 Pioneer 3394	Waxy	LSD[b]
Starch					
Modified 100-g	62.4b,n ± 0.36	68.1b,n ± 0.47	66.3c,n ± 0.64	60.4a,o ± 0.33	0.8
1-Kg	61.7b,n ± 0.76	67.4d,n ± 0.64	66.2c,n ± 0.56	59.1a,n ± 0.46	1.2
Pilot plant	59.0b,m ± 2.26	63.5c,m ± 1.41	62.7c,m ± 0.32	52.4a,m ± 0.98	2.0
LSD[c]	1.6	1.9	0.9	1.3	
Gluten					
Modified 100-g	11.8b,m,n ± 0.90	9.6a,m,n ± 0.67	9.2a,n ± 0.35	12.3b,n ± 0.56	0.8
1-Kg	10.7b,n ± 0.42	8.3b,m ± 0.10	7.3a,m ± 0.12	10.1b,m ± 1.19	1.2
Pilot plant	13.3b,n ± 0.67	10.5a,n ± 1.06	11.1a,o ± 0.60	16.9c,o ± 0.95	1.5
LSD	1.5	1.4	0.8	1.9	
Germ					
Modified 100-g	3.9b,m ± 0.47	3.3a,m ± 0.81	5.1c,n ± 0.09	6.5d,m ± 0.24	0.6
1-Kg	5.1a,m ± 0.38	5.4a,o ± 0.25	5.3a,n ± 0.49	6.2b,m ± 0.51	0.8
Pilot plant	5.3b,n ± 0.21	4.6a,n ± 0.14	4.3a,m ± 0.26	6.1c,m ± 0.48	0.4
LSD	0.7	0.6	0.6	0.7	
Fiber					
Modified 100-g	11.9a,m ± 1.13	11.7a,m ± 0.69	10.9a,m ± 0.36	11.6a,m ± 0.21	1.4
1-Kg	12.1b,m ± 0.83	11.5a,b,m ± 0.38	10.4b,m ± 1.26	12.6a,m ± 0.42	1.1
Pilot plant	14.1a,m ± 2.12	13.6a,n ± 1.22	12.7a,n ± 0.51	13.7a,n ± 0.64	2.4
LSD	2.9	1.7	1.1	1.2	

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[a] Values reported on a dry basis. Means of three observations ± one standard deviation.

[b] Least significant difference. Values in the same row with different letters (a-d) are significantly different ($P < 0.05$).

[c] Values in the same column with different letters (m-o) are significantly different ($P < 0.05$).

[d] Inseparables for the 1-Kg procedure and pilot-plant procedures were compared using the *t*-test.

[e] Not available because the fraction is not produced in the procedure.

Table II. (Continued)

Fraction/Procedure	Hybrids Pioneer 3245	 Pioneer 3317	 Pioneer 3394	Waxy	LSD[b]
Inseparables[d]					
Modified 100-g	NA[c]	NA	NA	NA	NA
1-Kg	0.23a,m ±0.07	0.36a,b,m ± 0.02	0.60b,c,m ± 0.18	0.73b,m ± 0.12	0.2
Pilot plant	2.1a,n ± 0.67	1.6a,n ± 0.07	2.8b,n ± 0.26	2.9b,n ± 0.28	0.7

TABLE III

Starch Recoveries (% db) for the Three Wet-Milling Procedures[a]

Procedure	Hybrids Pioneer 3245	 Pioneer 3317	 Pioneer 3394	Waxy	LSD[b]
Modified 100-g	86.7b,n ± 0.50	94.0d,n ± 0.65	92.3c.n ± 0.47	83.9a,n ± 0.46	1.0
1-Kg	85.8b,m,n ± 1.05	93.1c,n ± 0.88	92.1c,n ± 0.77	82.1a,n ± 0.64	1.6
Pilot plant	82.0b,m ± 3.13	87.7c,m ± 1.95	87.2c,m ± 0.45	73.0a,m ± 1.37	3.7
LSD[c]	3.9	2.6	1.2	6.9	

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[a] Values reported on a dry basis. Means of three observations ± one standard deviation.

[b] Least significant difference. Values in the same row with different letters (a-d) are significantly different ($P < 0.05$).

[c] Values in the same column with different letters (m-o) are significantly different ($P < 0.05$).

TABLE IV
Yields (% db) of Liquid Wet-Milling Fractions[a]

Fraction/Procedure	Hybrids Pioneer 3245	 Pioneer 3317	 Pioneer 3394	Waxy	LSD[b]
Light-steep-liquor solids					
Modified 100-g	4.4b,m ± 0.01	3.8a,m ± 0.23	4.6c,m ± 0.02	4.9d,m ± 0.09	0.2
1-Kg	6.9b,n ± 0.06	6.1a,n ± 0.32	7.7c,m ± 0.12	7.5c,o ± 0.31	0.4
Pilot plant	8.1b,n ± 1.65	6.1a,n ± 0.04	7.5b,a ± 0.90	6.7b,n ± 0.25	2.0
LSD[c]	1.9	1.3	1.0	0.5	
Filtrate water solids[d]					
Modified 100-g	3.8b,n ± 0.26	3.1a,n ± 0.18	3.0a,n ± 0.08	3.6b,n ± 0.22	0.4
1-Kg	2.1a,m ± 0.21	2.3a,b,m ± 0.40	2.0a,m ± 0.21	2.7b,m ± 0.33	0.6
Pilot plant	ND[e]	ND	ND	ND	ND
Rinse water solids					
Modified 100-g	NA[f]	NA	NA	NA	NA
1-Kg	NA	NA	NA	NA	NA
Pilot plant	0.67a ± 0.29	0.57a ± 0.02	0.64a ± 0.48	0.93a ± 0.33	0.60
Total-dissolved solids					
Modified 100-g	8.2a,m ± 0.26	7.0a,m ± 0.19	7.6a,m ± 0.10	8.5a,m ± 0.23	1.8
1-Kg	9.0b,m ± 0.23	8.4a,n ± 0.10	9.7c,n ± 0.81	10.2d,m,n ± 0.0	0.37
Pilot plant	ND	ND	ND	ND	ND

[a] Values are reported on a dry basis. Means of three observations ± one standard deviation.

[b] Least significant difference. Values in the same row with different letters (a-d) are significantly different ($P < 0.05$).

[c] Values in the same column with different letters (m-o) are significantly different ($P < 0.05$).

[d] Filtrate water solids for the 1-Kg procedure and the pilot-plant procedure were compared using the *t*-test.

[e] Not available because the fraction is not produced in the procedure.

[f] Data are the sum of the light-steep-liquor solids and filtrate water solids.

TABLE V
Protein Contents (% db) of Wet-Milling Fractions[a]

Fraction/Procedure	Hybrids Pioneer 3245	Pioneer 3317	Pioneer 3394	Waxy	LSD[b]
Starch					
Modified 100-g	0.29b,m ± 0.02	0.29b,m ± 0.04	0.34b,n ± 0.06[b,n]	0.18a,m ± 0.01	0.07
1-Kg	0.41c,n ± 0.02	0.29b,m ± 0.03	0.30b,m,n ± 0.04	0.22a,n ± 0.03	0.05
Pilot plant	0.32c,m ± 0.02	0.24b,m ± 0.01	0.25b,m ± 0.00	0.18a,m ± 0.00	0.02
LSD[c]	0.04	0.06	0.09	0.04	
Gluten					
Modified 100-g	46.9c,m ± 0.89	42.3b,m ± 1.82	41.1b,m ± 3.79	34.1a,m ± 2.54	4.7
1-Kg	44.2c,m ± 1.68	39.0a,m ± 1.60	44.0c,m ± 2.75	36.8a,m ± 0.65	3.4
Pilot plant	42.7a,m ± 3.29	37.1a,b,m ± 4.64	36.0b,m ± 3.61	24.8c,n ± 2.04	6.6
LSD	4.4	7.2	5.6	3.8	
Germ[d]					
Modified 100-g[e]	IM[f]	IM	IM	IM	IM
1-Kg	14.1b,m ± 0.70	14.1b,m ± 0.72	15.2c,m ± 0.35	12.8c,m ± 0.06	1.0
Pilot plant	15.0b,m ± 0.51	15.4b,m ± 0.71	15.3b,m ± 0.25	12.6a,m ± 0.95	1.2
Fiber					
Modified 100-g	IM	IM	IM	IM	IM
1-Kg	13.2b,m ± 0.26	11.7a,n ± 0.46	11.6a,m ± 0.57	11.9a,m ± 0.38	0.8
Pilot plant	11.5b,m ± 0.36	10.3a,m ± 0.58	10.8a,b,m ± 0.59	10.7a,b,m ± 0.56	1.2

[a] Values are reported on a dry basis. Means of three observations ± one standard deviation.

[b] Least significant difference. Values in the same row with different letters (a-d) are significantly different ($P < 0.05$).

[c] Values in the same column with different letters (m-o) are significantly different ($P < 0.05$).

[d] Germ, fiber, light-steep-liquor solids, and inseparable fractions for the 1-Kg and the pilot-plant procedures were compared with the *t*-test.

[e] In the modified 100-g procedure, the protein content was determined only for starch and gluten.

[f] Insufficient material in the fraction to allow determination.

[g] Not available because the fraction is not produced in the procedure.

[h] Not determined because suitable pilot-plant equipment for gluten filtration was unavailable.

Table V. (Continued)

Fraction/Procedure	Hybrids Pioneer 3245	 Pioneer 3317	 Pioneer 3394	Waxy	LSD[b]
Light-steep-liquor solids					
Modified 100-g	IM	IM	IM	IM	IM
1-Kg	30.8a,n ± 1.11	31.2a,n ± 2.18	27.7a,m ± 2.73	27.2a,m ± 0.85	3.5
Pilot plant	24.7a,b,m ± 0.75	23.1a,m ± 2.27	25.5a,b,m ± 1.16	26.9a,m ± 1.06	2.7
Inseparables					
Modified 100-g	NA[g]	NA	NA	NA	NA
1-Kg	3.8c,m ± 0.59	1.1b,m ± 0.20	1.3b,m ± 0.07	0.36a,m ± 0.12	0.6
Pilot plant	4.7b,m ± 1.56	0.7a,m ± 0.27	1.5a,m ± 0.28	0.23a,m ± 0.04	1.5
Filtrate solids					
Modified 100-g	IM	IM	IM	IM	IM
1-Kg	32.2a ± 1.21	44.8b ± 7.62	34.7a ± 5.62[a]	31.9a ± 3.12	9.5
Pilot plant	NA[h]	NA	NA	NA	NA

TABLE VI
Crude Free Fat Contents (% db) of Wet-Milling Fractions[a]

Fraction/Procedure[b]	Hybrids			Waxy	LSD[c]
	Pioneer 3245	Pioneer 3317	Pioneer 3394		
Starch					
1-Kg	0.05a,m ± 0.00	0.03a,m ± 0.02	0.05a,n ± 0.01	0.06a,m ± 0.04	0.04
Pilot plant	0.04a,m ± 0.02	0.05a,m ± 0.02	0.03a,m ± 0.01	0.07a,m ± 0.03	0.04
Gluten					
1-Kg	5.9a ± 0.92	8.4b ± 1.40	7.6ab ± 0.74	9.4b ± 1.19	2.1
Pilot plant	NA[e]	NA	NA	NA	NA
Germ					
1-Kg	53.8b,m ± 3.58	39.2am ± 4.53	40.8a,m ± 3.14	42.6a,m ± 5.86	8.3
Pilot plant	55.0b,m ± 3.20	47.1a,n ± 1.77	43.3a,m ± 1.38	44.9a,m ± 1.97	4.2
Fiber					
1-Kg	3.0a,m ± 0.35	3.1a,m ± 0.46	3.4a,b,m ± 0.75	4.6b,m ± 1.01	1.3
Pilot plant	2.6a,m ± 0.15	3.7b,m ± 0.23	4.4c,m ± 0.18	3.7b,m ± 0.12	0.3
Inseparables					
1-Kg	0.29b,n ± 0.08	0.15a,b,m ± 0.08	0.18a,b,m ± 0.17	0.07a,m ± 0.01	0.19
Pilot plant	0.10a,m ± 0.04	0.12a,m ± 0.02	0.08a,m ± 0.01	0.07a,m ± 0.05	0.06

[a] Values are reported on a dry basis. Means of three observations ± one standard deviation. None of the fractions from the 100-g procedure were analyzed for crude free fat content because the procedure did not produce sufficient material for analysis.

[b] Fractions for the 1-Kg procedure and the pilot-plant procedure were compared with the *t*-test. Values in the same column with different letters (m-n) are significantly different ($P < 0.05$)

[c] Least significant difference. Values in the same row with different letters (a-d) are significantly different ($p < 0.05$).

[d] Not available because the fraction is not produced in the procedure.

List of Figure Captions

Fig. 1. Flow sheet for the modified 100-g laboratory wet-milling procedure.

Fig. 2. Flow sheet for the 1-Kg laboratory wet-milling procedure.

Fig. 3. Flow sheet for the 10-Kg pilot-plant wet-milling procedure.

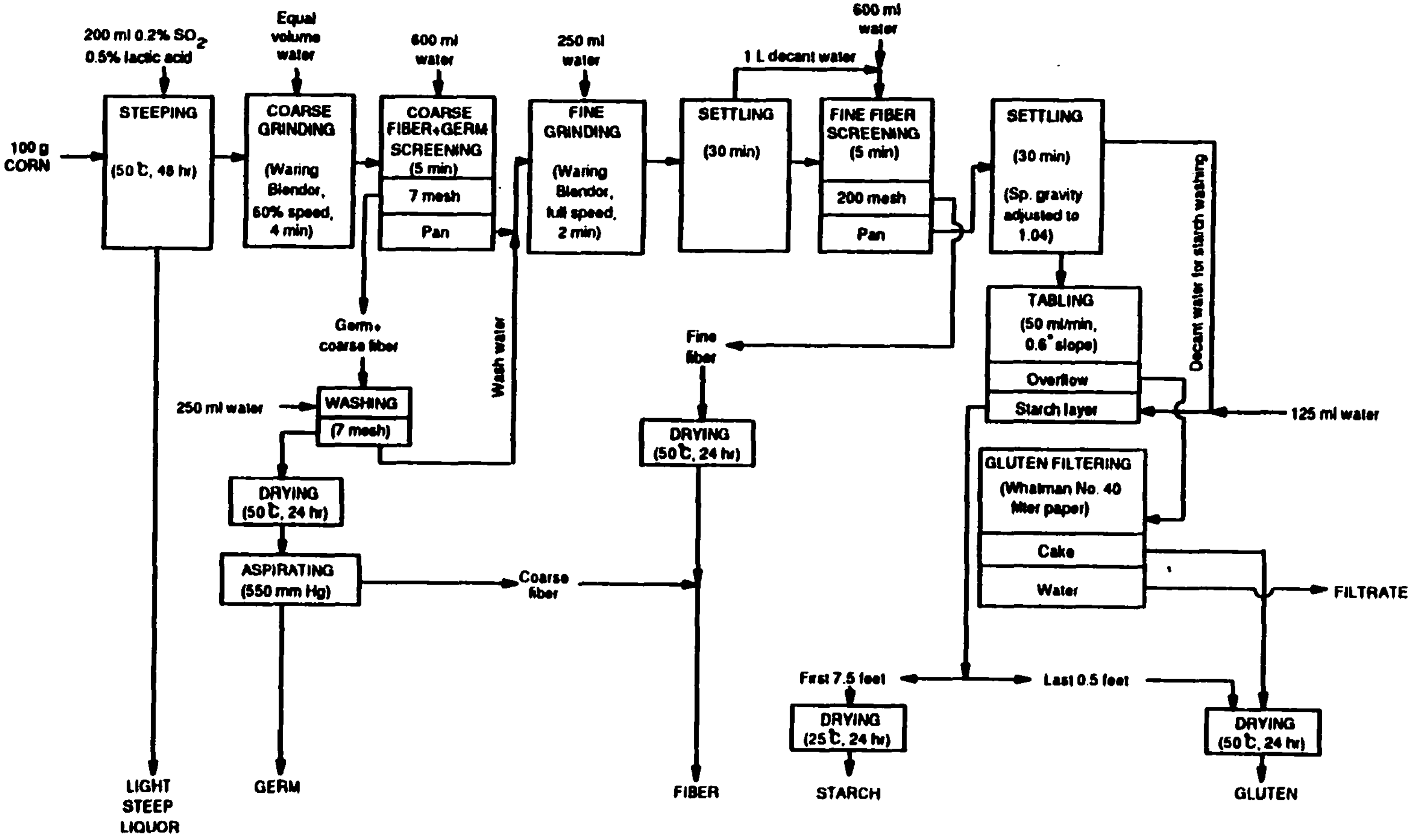
200 ml 0.2% SO2
0.5% lactic acid
Equal volume water
600 ml water
250 ml water
1 L decant water
600 ml water
100 g CORN
STEEPING
(50 ℃, 48 hr)
COARSE GRINDING
(Waring Blendor, 60% speed, 4 min)
COARSE FIBER+GERM SCREENING
(5 min)
7 mesh
Pan
FINE GRINDING
(Waring Blendor, full speed, 2 min)
SETTLING
(30 min)
FINE FIBER SCREENING
(5 min)
200 mesh
Pan
SETTLING
(30 min)
(Sp. gravity adjusted to 1.04)
Decant water for starch washing
Germ+ coarse fiber
Wash water
Fine fiber
TABLING
(50 ml/min, 0.6° slope)
Overflow
Starch layer
125 ml water
250 ml water
WASHING
(7 mesh)
DRYING
(50 ℃, 24 hr)
DRYING
(50 ℃, 24 hr)
GLUTEN FILTERING
(Whatman No. 40 filter paper)
Cake
Water
FILTRATE
ASPIRATING
(550 mm Hg)
Coarse fiber
First 7.5 feet
Last 0.5 feet
DRYING
(25 ℃, 24 hr)
DRYING
(50 ℃, 24 hr)
LIGHT STEEP LIQUOR
GERM
FIBER
STARCH
GLUTEN

Fig. 1.

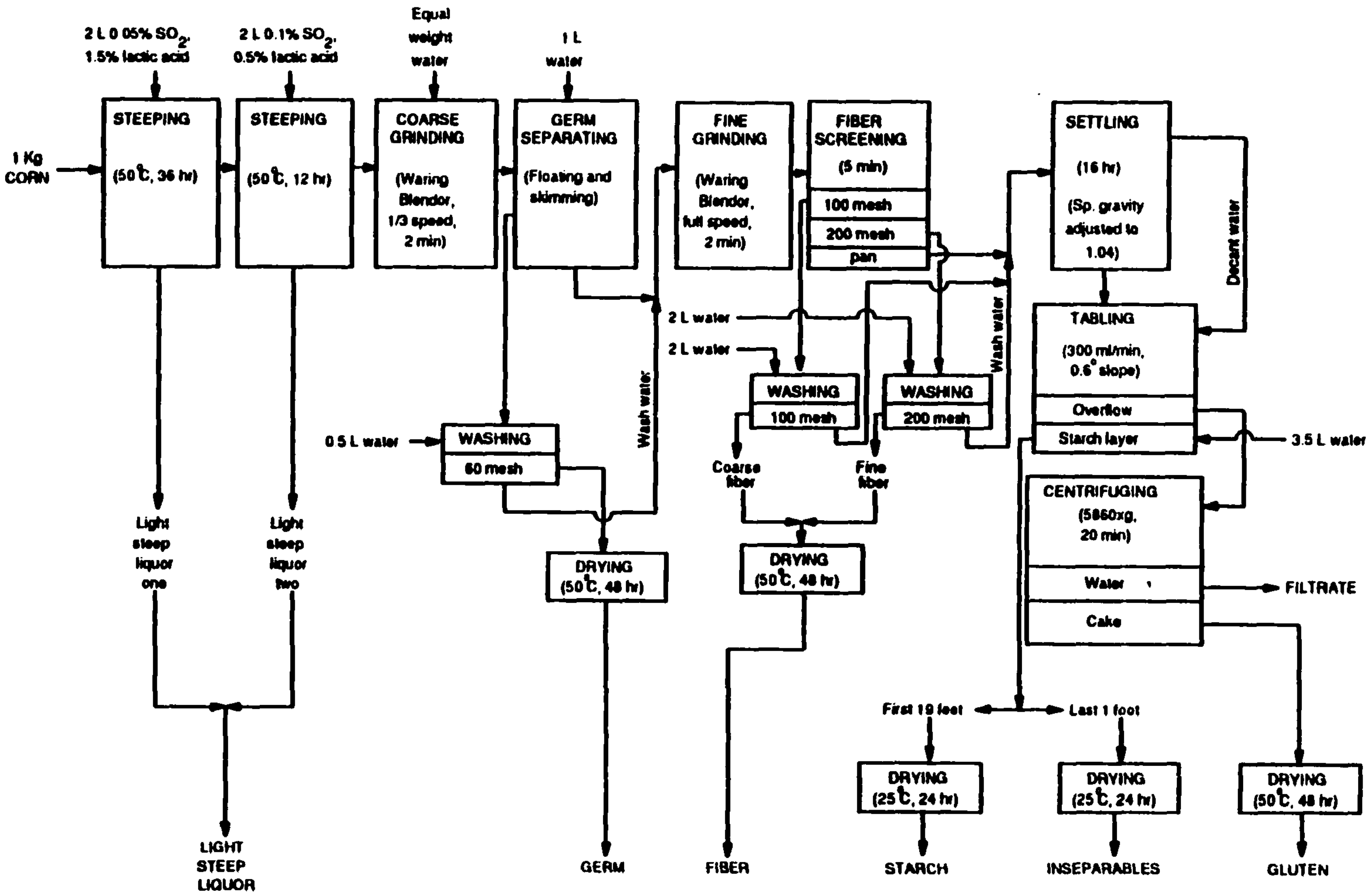
2 L 0.05% SO_2, 1.5% lactic acid
2 L 0.1% SO_2, 0.5% lactic acid
Equal weight water
1 L water
1 Kg CORN
STEEPING (50℃, 36 hr)
STEEPING (50℃, 12 hr)
COARSE GRINDING (Waring Blendor, 1/3 speed, 2 min)
GERM SEPARATING (Floating and skimming)
FINE GRINDING (Waring Blendor, full speed, 2 min)
FIBER SCREENING (5 min)
100 mesh
200 mesh
pan
SETTLING (16 hr) (Sp. gravity adjusted to 1.04)
Decant water
TABLING (300 ml/min, 0.6° slope)
Overflow
Starch layer
3.5 L water
CENTRIFUGING (5860xg, 20 min)
Water
Cake
FILTRATE
Wash water
2 L water
2 L water
WASHING 100 mesh
WASHING 200 mesh
Wash water
0.5 L water
WASHING 60 mesh
Coarse fiber
Fine fiber
DRYING (50℃, 48 hr)
DRYING (50℃, 48 hr)
Light steep liquor one
Light steep liquor two
LIGHT STEEP LIQUOR
GERM
FIBER
First 19 feet
Last 1 foot
DRYING (25℃, 24 hr)
DRYING (25℃, 24 hr)
DRYING (50℃, 48 hr)
STARCH
INSEPARABLES
GLUTEN

Fig. 2.

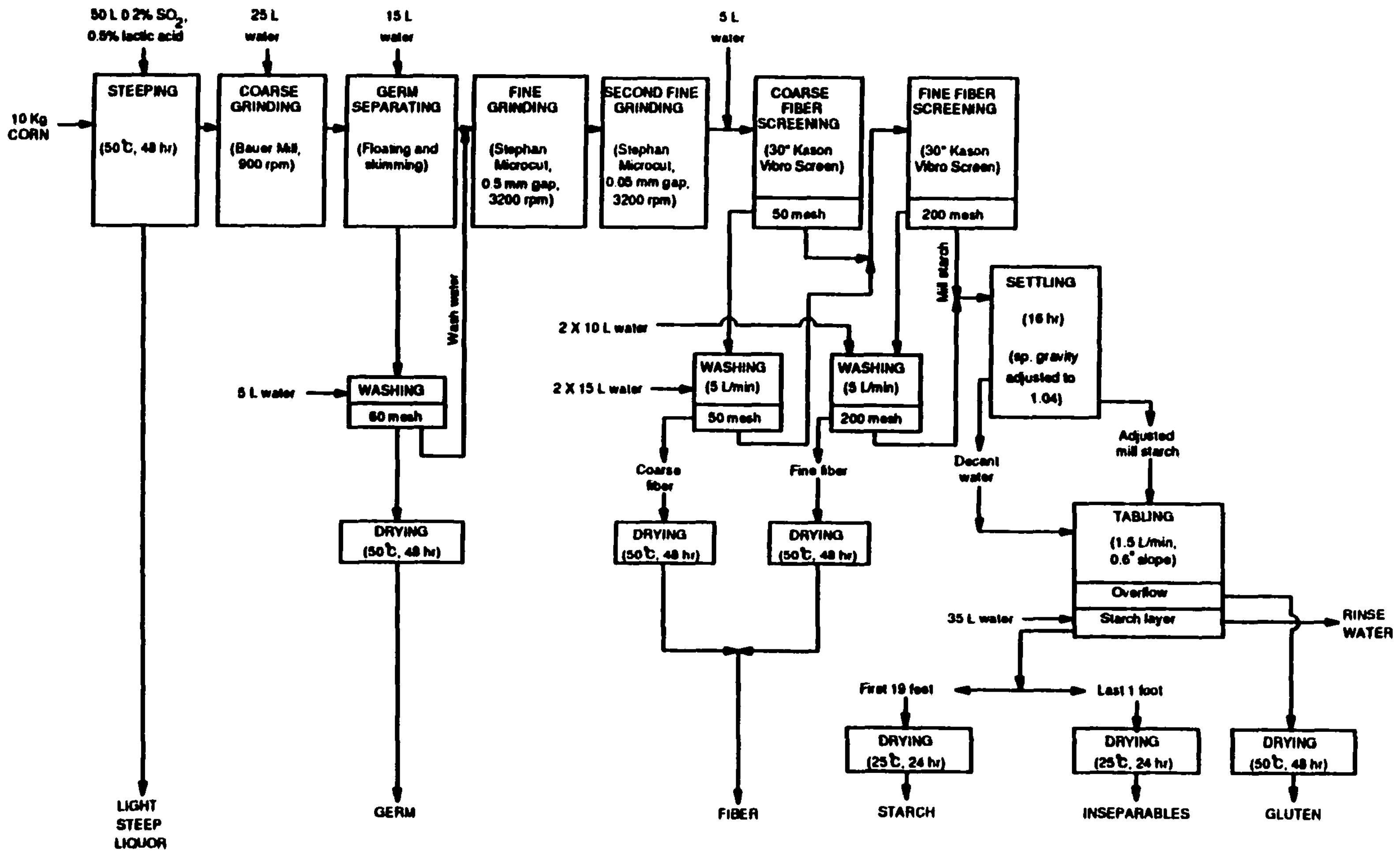
50 L 0.2% SO_2, 0.5% lactic acid
25 L water
15 L water
5 L water
10 Kg CORN
STEEPING
(50℃, 48 hr)
COARSE GRINDING
(Bauer Mill, 900 rpm)
GERM SEPARATING
(Floating and skimming)
FINE GRINDING
(Stephan Microcut, 0.5 mm gap, 3200 rpm)
SECOND FINE GRINDING
(Stephan Microcut, 0.05 mm gap, 3200 rpm)
COARSE FIBER SCREENING
(30" Kason Vibro Screen)
50 mesh
FINE FIBER SCREENING
(30" Kason Vibro Screen)
200 mesh
Wash water
Mill starch
SETTLING
(16 hr)
(sp. gravity adjusted to 1.04)
2 X 10 L water
2 X 15 L water
5 L water
WASHING
60 mesh
WASHING
(5 L/min)
50 mesh
WASHING
(5 L/min)
200 mesh
Coarse fiber
Fine fiber
Decant water
Adjusted mill starch
DRYING
(50℃, 48 hr)
DRYING
(50℃, 48 hr)
DRYING
(50℃, 48 hr)
TABLING
(1.5 L/min, 0.6° slope)
Overflow
Starch layer
35 L water
RINSE WATER
First 19 feet
Last 1 foot
DRYING
(25℃, 24 hr)
DRYING
(25℃, 24 hr)
DRYING
(50℃, 48 hr)
LIGHT STEEP LIQUOR
GERM
FIBER
STARCH
INSEPARABLES
GLUTEN

Fig. 3.

COMPOSITIONAL, PHYSICAL, AND WET-MILLING PROPERTIES OF ACCESSIONS USED IN THE GERMPLASM ENHANCEMENT OF MAIZE PROJECT[1]

S.K. Singh[2], L.A. Johnson[3], L.M. Pollak[4], and C. R. Hurburgh[5],

ABSTRACT

Forty-nine accessions from the Latin American Maize Project (LAMP), two commercial hybrids (Pioneer 3394 and Pioneer 3489), and two Corn-Belt inbreds were evaluated for their compositional, physical, and wet-milling properties. Most of the accessions in LAMP had high yields and thus are being used in the Germplasm Enhancement Maize Project (GEM), or are slated to be used in the future. The GEM accessions had lower starch contents (65.9-69.1% versus a mean of 72.2% for two

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commercial hybrids) and greater protein contents (12.0-14.4% versus a mean of 8.2% for two commercial hybrids) than the improved Corn-Belt material. Absolute densities were consistently higher for the GEM accessions compared to the commercial hybrids (1.320 versus 1.265 g/cc, respectively). The wet-milling characteristics of the GEM accessions were not nearly as good as for the commercial hybrids. Mean starch yields were only 54.3% for the GEM accessions versus 64.8% for the commercial hybrids. Residual protein levels in the starches recovered from the GEM accessions were much greater (0.45-2.03%) than for commercial corn hybrids (< 0.3%). Gluten yields were much greater for the GEM accessions than for the commercial hybrids due to higher starch contents of the gluten fractions, which reduced starch recovery and the protein contents of gluten. High fiber yields for the GEM accessions indicating that the starch did not separate easily from the fiber as well. The selected accessions did not contain unique traits, but breeders could utilize their wide variation of properties to develop unique lines. In addition, traits that made them less suitable for wet milling than the improved Corn-Belt material may make them more suitable breeding material for other uses than are adapted hybrids.

INTRODUCTION

Processing continues to consume increasing amounts of corn. Utilization of corn for starch, sweeteners, ethanol, and other fermentation products now consumes more than 17% of the yearly production, most of which involves wet milling. Corn hybrids with improved wet-milling characteristics and unique starch properties have been of great interest to seed companies, wet millers, and end users of starch and other wet-milled corn products. High-yielding hybrids with higher contents of starch, protein and/or oil in the kernel have been developed, but little has been done to improve the millability of corn, proximate compositions of the recovered fractions, and the physical properties of corn important to grain processing.

High-yielding U.S. corn hybrids with improved agronomic traits have been developed by using adapted germplasm, but seldom have elite inbreds successfully been crossed with exotic corn germplasm to develop new useful breeding lines. The Germplasm Enhancement of Maize Project (GEM) is a unique cooperation of the public and private sectors, which has initiated efforts to strengthen U.S. corn hybrids for increased yields, agronomic characteristics, and value-added traits (Pollak and Salhuana 1998). GEM is the successor to the Latin American Maize Project (LAMP) (Salhuana et al 1998), which was launched in 1987 by the U.S. Department of Agriculture, Agriculture Research Services (USDA/ARS) and 12 Latin American countries with funding from Pioneer Hi-Bred International (Johnston, IA). The principle goal of LAMP was to evaluate and maintain the irreplaceable corn germplasm bank of 12 Latin American countries and the United States.

LAMP evaluated 12,000 accessions grown at 70 locations in the United States and Latin America. Screening was done on the basis of yield potential and agronomic characteristics. Two hundred sixty-eight of these accessions were selected as potential sources of high yields, then 51 were chosen to initiate GEM. Fox et al (1992) and Zehr et al (1995) have shown considerable variation in compositional, physical, and wet-milling properties in yellow dent hybrids and inbreds, thus we anticipated greater variation among the GEM accessions because of their diverse genetic background. The objective of the present study was to screen 49 GEM or future GEM accessions of U.S. and Latin

American origin for their compositional, physical, and wet-milling properties to identify accessions with unique properties that could be used to develop new lines with value-added traits.

MATERIALS AND METHODS

Grain Preparation

Forty-five Latin-American and U.S. accessions were evaluated in this experiment (Table 1). Five of the 51 original GEM accessions were not included in the study because of insufficient seed supply. Substitutions were made with four accessions from the top 5% selected LAMP accessions from Peru (Lima 13, Lambayeque 46, Piura 196, and San Martin 116), which will be part of GEM in the future. The accessions (North Central Regional Plant Introduction Station, Ames IA), two commercial yellow dent corn hybrids (3394 and 3489 from Pioneer Hi-Bred International, Inc., Johnston, IA), and two public Corn-Belt inbreds, B73 and Mo17 (Department of Agronomy, Iowa State University, Ames, IA) were dried to <15% moisture by circulating ambient air (20-22 °C) and cleaned by passing through a 6.35-mm round-hole U.S. standard sieve. Any remaining foreign material and broken kernels were removed by hand. Triplicate sample sets were prepared, placed into polyethylene bags, and stored at 4 °C until used.

Compositional Properties

Moisture contents of the corn were determined by using AACC method 44-15A (AACC 1983). Starch, protein, and crude free fat contents (dry basis) were estimated in triplicate by using an Infratec Grain Analyzer, a near-infrared transmittance (NIR-T) analyzer (Tecator, Hoganas, Sweden).

Physical Properties

Kernel absolute density was determined by using an AccuPyc 1330 pycnometer (Micrometrics, Norcross, GA). Test weight was determined by using Federal Grain Inspection Services (FGIS 1988) standard methods. Thousand-kernel weight was determined by using an electronic counter (Syntron, Homer City, PA) to count kernels and weighing on an analytical balance. Values were determined in triplicate and adjusted to 15% moisture basis by using adjustment equations for moisture reported by Dorsey-Redding et al (1990).

Wet-Milling Properties

Corn was wet milled in triplicate by using a 100-g laboratory-scale wet-milling procedure originally developed by Eckhoff et al (1996) and modified by Singh et al (1997). Moisture contents of the wet-milled fractions were determined according to AOAC method 14.004 (AOAC 1984). Protein contents of the wet-milled fractions were determined in duplicate according to the Corn Refiners' Association macro-Kjeldahl method A-18 (CRA 1986). Because of the limited amount of each fraction available when using the modified 100-g procedure, only the starch and gluten fractions were analyzed for protein contents.

Statistical Analysis

Unpaired parametric, multiple comparison tests (SAS 1984) were used to determine least significant differences (LSD) at $P<0.05$, 0.01, and 0.001 levels. SAS procedure CORR was used to determine correlations.

RESULTS AND DISCUSSION

Compositional, physical, and wet-milling properties of the GEM accessions varied greatly (Tables II and III). Properties of the GEM accessions were compared with two commercial dent hybrids and two Corn-Belt inbreds in the form of frequency distribution histograms, where the X-axis represents the range of values observed for the property and the Y-axis represents the number of observation for a given range of values. The height of the column represents the number of accessions falling within the specified range (column width).

Compositional properties

Generally, the GEM accessions contained less starch in the grain than either of the two commercial hybrids or the two Corn-Belt inbreds. The starch contents of the GEM accessions ranged from 65.9 to 69.1% (db) versus 71.1-73.3 % for the two commercial dent hybrids and 68.0-69.7% for the two Corn-Belt inbreds, (Fig. 1A). The highest and lowest starch contents among the GEM accessions were observed in Golden Queen and Cuba 110, respectively. Zehr et al (1995) observed that starch yields upon wet milling increased as starch contents increased, Fox et al (1992) did not observe high correlation between starch yield and starch content, and concluded that the composition of protein present must also affect wet-milling properties.

The GEM accessions had considerably greater grain protein contents, having a mean value of 13.0% (db) for GEM versus 8.15% for the two commercial dent hybrids (Fig. 1B). High protein content (especially that due to increased endosperm protein) generally leads to poor wet-milling properties (Fox et al 1992). The lowest and greatest protein contents were 7.7% for Pioneer 3394 and 14.4% for Cuba 110, respectively. Cuba 110 also had the lowest starch and greatest fat contents (65.9 and 6.2%, respectively). Pioneer 3489 and B73 had relatively low protein contents, but Mo17 had relatively high protein content.

The GEM accessions had considerably greater fat contents than did the commercial dent hybrids and the Corn-Belt inbreds, having a mean of 5.2% versus 3.85 and 4.05% for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively (Fig. 1C). Pioneer 3394 had the lowest, and Cuba 110 had the highest fat content (3.4 and 6.5%, respectively). Pioneer 3489, B73, and Mo17 had moderately low fat contents.

While not measured directly, the higher protein and fat contents suggest that the GEM accessions have greater proportions of germs, which may be valuable in breeding "high-oil" lines. Increased germ size may be important to corn destined for feeding livestock because of greater contents of protein and metabolizable energy. Increased protein due to larger germs should not adversely affect starch/gluten separation as would endosperm protein. However, corn with larger germs can adversely affect processing efficiency in wet mills because of increased germ mass and less starch mass per unit of corn.

Physical Properties

The 1000 kernel weights of the GEM accessions varied quite widely (240 to 316 g); but, the mean for the GEM accessions was lower than for the commercial dent hybrids. Thus, fiber yields in wet milling were expected to be greater, and yields of starch and gluten were expected to be less for the GEM accessions because GEM kernels have greater ratios of surface area to mass. Test weights of the GEM accessions varied from 52.4 to 68.2 lb/bu, but on average, were nearly equivalent to the two commercial dent hybrids. Mo17 had lower test weight (60.9 lb/bu) and 1000 kernel weight (205.1 g).

The absolute densities of the GEM accessions were considerably greater than for either the commercial dent hybrids or the Corn-Belt inbreds, averaging 1.32 g/cc for the GEM accessions versus 1.27 and 1.29 g/cc for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively (Fig. 1D). The lowest (1.17 g/cc) and greatest (1.37 g/cc) absolute densities were observed in Piura 196 and 789357, respectively. Increased absolute density of the kernel may adversely affect wet-milling properties (Zehr et al 1995), unless protein content is also decreased (Fox et al 1992). This combination of traits was not observed in the GEM accessions. Absolute densities of Pioneer 3394 and 3489 were within the lower 20%. B73 and Mo17 had greater absolute densities than did the commercial dent hybrids.

Wet-milling Properties

The GEM accessions did not wet mill nearly as well as did the commercial dent hybrids (Fig. 2A). Starch yields averaged only 54.3% for the GEM accessions versus 64.9% for the two commercial dent hybrids and 60.2% for the two Corn-Belt inbreds, which was attributed to higher protein contents, kernel densities, and residual starch contents in fiber. Starch yield was greatest for Pioneer 3394, followed by Pioneer 3489 and B73. Mo17 yielded significantly less starch (58.1%) than did the two commercial dent hybrids or B73. The highest and lowest starch yields among the GEM accessions were achieved by Piura 196 (61.9%) and Cuba 110 (47.8%), respectively.

Starch recovery, which is the percentage ratio of starch yield divided by starch content, was greatest for Piura 196, followed by Pioneer 3394, B73, and Pioneer 3489 (Fig. 2B). Mo17 did not compare well with B73 and the commercial dent hybrids. Piura 196 yielded the highest amount of starch among the GEM accessions, despite having relatively low starch content in the kernel. This accession had low absolute density and protein and fat contents which favor good wet milling. The lowest starch recovery was observed in Dominican Republic 269, which had relatively high protein content, low starch content, and high absolute density. The poor fiber-washing characteristics of Dominican Republic 269 resulted in lower starch and higher fiber yields. Protein contents of the starch were much greater than the usual acceptable limits (<0.3%) for all GEM accessions (averaging 1.05%) except for ARZM 01150 and ARZM 03056.

Gluten yields were much greater for the GEM accessions, averaging 14.9% versus 8.6 and 12.4% for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively. This was attributed to the high kernel protein contents and poor starch-gluten separation. The lowest gluten yield was achieved by Pioneer 3394 followed by Pioneer 3489, ARZM 01150, and B73 (Fig. 2C). Mo17 yielded moderately high amounts of gluten compared with the commercial dent hybrids and B73. Poor starch-gluten separation in Mo17 also resulted in reduced protein contents in gluten and increased protein contents in starch. Mo17 did not have good wet-milling properties and thus its modern descendents may not be the best choices to use as an inbred parent for producing hybrids destined to wet corn mills, unless the hybrid's other inbred parents had dominant genes for good wet milling properties. We observed in poor wet-milling corn that the protein particles did not flow as discrete particles during the tabling of the millstarch, rather they tended to flocculate and deposit on the surface of the starch bed.

Low protein contents of the gluten fraction were observed in the GEM accessions, averaging 42.4% versus 44.5 and 49.7% for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively. Poor starch-gluten separation among the GEM accessions produced greater gluten yields with greater amounts of starch in gluten resulting in low protein contents in the gluten.

Fiber yields were much greater for the GEM accessions (Fig 2D), averaging 14.6% versus 11.7 and 11.9% for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively, which we attributed to poor fiber-washing characteristics and low 1000 kernel weights (less volume to surface area, less endosperm to pericarp). Lowest fiber yield was observed for Piura 196 followed by Pioneer 3394, B73, Mo17, and Pioneer 3489, respectively. Poor fiber-washing characteristics of GEM accessions resulted in reduced starch yields and recoveries.

Despite having greater mean kernel oil contents, germ yields were lower for the GEM accessions, a mean of 3.05% versus means of 4.6 and 5.9% for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively. Despite previous comments about proportion of germs in GEM grain, this suggests that the GEM accessions do not have greater proportions of germ than typical of Corn-Belt dent corn.

Single Factor Correlation

Table IV shows correlation coefficients between wet-milling properties and compositional and physical properties based on the 49 GEM accessions. Starch yield and recovery were positively correlated with starch content, and negatively correlated with protein content and absolute density. Zehr et al (1995) found similar correlations for 15 inbred lines. Based on 27 hybrids, Fox et al (1992) could not establish significant correlation of starch yield and starch recovery with starch content and absolute density, but did find a negative correlation of protein content with starch yield and recovery. Starch yields were also negatively correlated with fat content, 1000 kernel weight, and test weight.

Residual protein content in starch was positively correlated with kernel protein content, fat content, and absolute density. Fox et al (1992) found similar correlations based on 25 commercial dent hybrids. The residual protein content of starch was negatively correlated with starch content of the GEM accessions. Protein in starch was also correlated with test weight.

Gluten yields were positively correlated with protein content and negatively correlated with starch content. Similar results were observed by Zehr et al (1995); but, Fox et al (1992) did not observe correlation between gluten yield and starch content. Gluten yield was also positively correlated with absolute density and test weight, and negatively correlated with 1000 kernel weight.

CONCLUSIONS

GEM accessions did not wet mill nearly as good as commercial dent hybrids, which we attributed to several compositional and physical factors. The GEM accessions had considerably lower starch contents and greater protein and fat contents than did the commercial dent hybrids and the Corn-Belt inbreds. The higher levels of protein and fat in the kernels of the GEM accessions indicated that they are energy dense and are good for animal feed.

Increased grain protein contents resulted in increased absolute densities, which adversely affected wet-milling properties but would likely improve dry-milling characteristics. Absolute densities and test weights of the GEM accessions were correlated with most of the wet-milling yields and proximate factors. Lower absolute density corn showed improved millability, but it could result in poor grain handling properties.

These data suggest that the best GEM accessions for wet milling are those with lower absolute densities and test weights, greater starch contents, and lower fat and protein contents. Poor starch-gluten separation resulted in greater protein content in starch and lower protein content in gluten. Greater fiber yields of GEM accessions indicated poor fiber-washing characteristics.

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TABLE I
Descriptions of 49 GEM Accessions

Accession names	PI	Race	Kernel Color/Type	Area of Adaptation	Source
Cash	278710	Corn-Belt Dent	Yellow Dent	Temperate	USA, Ohio
Golden Queen	452040	Corn-Belt Dent	Yellow Dent	Temperate	USA, Ohio
Big White	452054	Southern Dent	White Dent	Temperate	USA, Tennessee
CHZM 04030	467139	Camelia	Orange Flint	Temperate	Chili, Coquimbo
CHZM 05015	467165	Camelia	Orange Flint	Temperate	Chili, Valparaiso
URZM 01089	479145	Cateto Sulino	Orange Flint	Temperate	Uruguay
Cuba 117	483816	Argentino	Orange Flint	Tropical	Cuba
Dominican Republic 150	484028	Mixed	Yellow Semident	Tropical	Dominican Republic
St. Croix 1	484036	St. Croix	Yellow Semident	Tropical	Virgin Islands (US)
Antigua 3	484991	Criollo	Yellow Semident	Tropical	Antigua & Barbuda
Lima 13	485347	Perla	Orange Flint	Tropical	Peru, Lima
Cuba 110	489357	Argentino	Orange Flint	Tropical	Cuba
Cuba 164	489361	Mixed	Orange Semiflint	Tropical	Cuba
Dominican Republic 269	489678	Canilla	Yellow Semident	Tropical	Dominican Republic
ARZM 01150	491741	Dent. Blanco Rugoso	White Dent	Temperate	Argentina, Buenos Aires
ARZM 03056	491799	Dentado Blanco	White Dent	Temperate	Argentina, Entre Rios
ARZM 13026	492746	Cristalino Colorado	Orange Flint	Temperate	Argentina, La Rioja
ARZM 13035	492753	Cristalino Colorado	Orange Flint	Temperate	Argentina, La Rioja
ARZM 17026	493012	Cristalino Colorado	Orange Flint	Temperate	Argentina, San Luis
ARZM 17056	493039	Cristalino Colorado	Orange Flint	Temperate	Argentina, San Luis
Guadelupe 5	498569	Early Caribbean	Yellow Flint	Tropical	Guadeloupe
Guatemala 209	498583	Tuson	Yellow Flint	Tropical	Guatemala
Lambayeque 46	503732	Arizona	White Dent	Tropical	Peru, Lima
Piura 196	503844	Alazan	Red/White cap flour	Tropical	Peru, Lima
Barbados Group 2	503885	Tuson	Yellow Dent	Tropical	Barbados
Puerto Rico Group 3	504142	Mixed	Yellow Dent	Tropical	Puerto Rico
St. Croix Group 3	504148	Tuson	Yellow Dent	Tropical	Virgin Islands (US)

Table I. (Continued)

Accession name	PI	Race	Kernel Color/Type	Area of Adaptation	Source
San Martin 116	515097	Cuban	Yellow Flint	Tropical	Peru, San Martin
ARZM 16021	516022	Cristalino Colorado	Orange Flint	Temperate	Argentina, Mendoza
ARZM 16026	516027	Cristalino Colorado	Orange Flint	Temperate	Argentina, Mendoza
ARZM 16035	516036	Cristalino Colorado	Orange Flint	Temperate	Argentina, Mendoza
FS8A(S)	536619	Mixed	Yellow Semident	Temperate	US, Florida
FS8A(T)	536620	Mixed	Yellow Semident	Temperate	US, Florida
FS8B(S)	536621	Mixed	Yellow Semident	Temperate	US, Florida
FS8B(T)	536622	Mixed	Yellow Semident	Temperate	US, Florida
Pasco 14	571679	Unclassified	Yellow Dent	Tropical	Peru, Pasco
Chiapas 462	583888	Hybrido Blanco	White Dent	Tropical	Mexico, Chiapas
British Virgin Islands 155	583901	Tuson	Yellow Dent	Tropical	Virgin Islands (British)
BRA 051403 (PE 01)	583911	Cateto	Orange Flint	Tropical	Brazil, Pernambuco
BRA 051501 (PE 011)	583912	Unclassified	Yellow Dent	Tropical	Brazil, Pernambuco
BRA 052051 (SE 32)	583917	Dente Amarelo	Yellow Dent	Tropical	Brazil, Sergipe
URZM 13061	583922	Cateto Sulino	Orange Flint	Temperate	Uruguay
URZM 13010	583923	Dente Branco	Orange Dent	Temperate	Uruguay
URZM 13088	583925	Cateto Sulino	Orange Flint	Temperate	Uruguay
URZM 13085	583927	Cateto Sulino	Orange Flint	Temperate	Uruguay
URZM 05071	583937	Riograndense	Orange Semident	Temperate	Uruguay
URZM 11002	583938	Dente Branco	White Dent	Temperate	Uruguay
URZM 10001	583942	Dente Branco	White Dent	Temperate	Uruguay
British Virgin Islands 103	586761	Criollo	Yellow Semiflint	Tropical	Virgin Islands (British)

TABLE II
Compositional, Physical, and Wet-Milling Properties of GEM Accessions[a]

Accession name	Compositional			Physical			Wet-Milling						
	Str (%db)	Pro (%db)	Fat (%db)	TWt (lb/bu)	KnWt (g)	ADen (g/cc)	StrY (%db)	PiS (%db)	SRec (%)	Glu (%db)	PiG (%db)	Germ (%db)	Fib (%db)
Cash	68.1	12.4	4.7	60.2	309.4	1.26	52.7	1.08	77.3	15.4	39.3	5.9	16.0
Golden Queen	69.1	12.4	4.0	63.1	329.8	1.28	58.6	0.83	84.7	12.9	45.1	5.8	12.4
Big White	69.0	12.2	4.8	60.3	310.4	1.30	58.8	0.69	85.2	14.7	38.4	3.7	12.7
CHZM 04030	68.4	12.5	4.8	64.2	248.1	1.35	51.6	1.02	75.4	19.4	38.1	4.7	13.5
CHZM 05015	66.7	13.3	5.4	64.4	309.2	1.34	48.9	1.65	73.3	20.1	34.1	5.3	15.7
URZM 01089	66.7	13.6	5.5	66.0	297.5	1.35	55.5	1.27	83.3	16.3	43.4	4.1	13.3
Cuba 117 Cuba	67.6	13.5	5.4	66.8	261.3	1.36	52.2	1.29	77.3	19.5	36.7	4.3	13.6
Dominican Republic 150	68.4	12.6	4.4	66.3	276.1	1.35	56.0	1.26	81.9	12.9	43.2	4.1	16.6
St. Croix 1	68.6	12.9	5.0	64.1	362.0	1.33	50.8	0.97	75.2	15.1	37.5	4.8	19.3
Antigua 3	67.8	12.7	5.3	66.5	330.5	1.35	53.1	0.97	78.4	13.9	43.8	4.3	16.9
Lima 13	66.7	13.8	5.5	52.3	305.4	1.33	53.7	1.01	80.5	14.9	41.8	3.1	17.0
Cuba 110	65.9	14.4	6.2	66.4	241.9	1.37	47.8	1.72	72.5	19.6	35.9	4.2	17.3
Cuba 164	68.6	12.5	4.9	65.6	271.8	1.34	55.5	0.81	80.6	16.0	40.1	3.8	14.7
Dominican Republic 269	67.9	13.5	4.7	65.8	271.9	1.34	48.4	1.49	71.3	15.9	38.2	6.0	17.5
ARZM 01150	68.9	12.6	4.5	55.7	261.5	1.26	58.4	0.47	84.7	11.2	45.6	9.6	12.0
ARZM 03056	68.3	12.7	5.0	57.9	302.8	1.28	57.1	0.45	83.6	12.5	45.0	6.7	13.4
ARZM 13026	68.3	12.2	4.9	63.0	334.8	1.34	51.0	1.15	74.7	18.6	40.5	4.7	13.0
ARZM 13035	66.2	13.8	5.5	64.2	303.9	1.35	51.5	1.17	77.9	19.1	43.3	5.7	13.9
ARZM 17026	67.3	13.2	5.2	63.4	306.2	1.33	54.3	1.06	80.7	15.8	46.6	5.2	12.8
ARZM 17056	67.8	13.1	4.5	60.2	279.5	1.33	53.0	1.07	78.2	17.2	43.1	5.3	14.5
Guadelupe 5	67.4	13.2	4.6	67.9	295.2	1.36	49.8	1.50	73.9	15.1	42.4	6.3	18.2
Guatemala 209	66.9	13.7	5.9	67.6	312.1	1.36	50.7	1.14	75.7	17.3	41.7	5.2	15.2
Lambayeque 46	68.3	12.6	5.0	57.3	350.8	1.25	58.9	0.88	86.3	14.2	45.6	5.3	11.8
Piura 196	66.6	12.0	3.9	56.9	291.5	1.17	61.9	0.57	92.9	12.9	51.0	3.4	10.6
Barbados Group 2	68.0	13.0	4.8	64.3	382.7	1.32	56.9	1.07	83.7	14.3	47.1	5.5	13.1
Puerto Rica Group 3	67.4	12.1	4.6	62.3	397.9	1.32	56.0	0.72	83.1	13.7	47.1	5.1	15.2
St. Croix Group 3	67.9	12.7	5.0	64.1	350.4	1.33	53.2	0.84	78.4	14.9	42.7	5.9	15.9

[a] Str = Starch content, Pro = Protein content, Fat = Crude free fat content, TWt = Test weight, KnWt = 1000 kernel weight, ADen = Absolute density, StrY = Starch yield, PiS = Protein in starch, SRec = Starch recovery, Glu = Gluten, PiG = Protein in gluten , and Fib = Fiber yield (% db).

[b] Least significant difference ($P < 0.05$).

Table II. (Continued)

Accession name	Compositional Str (%db)	Pro (%db)	Fat (%db)	Physical TWt (lb/bu)	KnWt (g)	ADen (g/cc)	Wet-Milling StrY (%db)	PiS (%db)	SRec (%)	Glu (%db)	PiG (%db)	Germ (%db)	Fib (%db)
San Martin 116	67.6	13.7	5.0	58.7	254.4	1.31	56.1	1.02	83.0	15.5	43.6	4.1	13.2
ARZM 16021	67.1	13.5	5.3	65.4	283.3	1.34	49.8	1.32	74.2	17.5	37.8	5.1	16.1
ARZM 16026	68.2	12.9	4.9	66.1	304.4	1.32	54.7	0.89	80.3	16.5	41.5	5.2	12.8
ARZM 16035	67.2	13.7	5.4	66.2	250.3	1.35	53.8	1.31	80.1	15.5	41.2	4.7	15.2
FS8A(S)	68.3	12.6	5.8	64.7	301.3	1.33	55.0	0.78	80.5	15.9	36.8	4.9	13.8
FS8A(T)	68.6	12.5	5.6	64.2	360.1	1.32	56.9	1.16	83.0	14.9	36.9	4.2	13.5
FS8B(S)	68.3	12.8	5.5	65.2	326.8	1.35	54.8	1.24	80.2	13.4	40.8	5.9	15.1
FS8B(T)	68.0	12.5	5.6	65.7	339.0	1.33	55.6	0.70	81.8	13.7	46.0	4.9	15.2
Pasco 14	66.3	13.6	5.7	68.2	326.6	1.36	51.7	0.91	78.0	15.4	42.5	4.2	16.9
Chiapas 462	67.5	13.5	5.2	63.4	392.6	1.32	54.7	1.12	79.8	11.8	47.4	6.0	14.9
British Virgin Islands 155	68.1	12.7	4.9	64.8	380.6	1.33	57.2	1.09	84.1	15.6	40.5	4.0	12.4
BRA 051403 (PE 01)	67.6	13.4	5.5	65.9	321.7	1.34	55.5	2.03	82.0	14.8	44.3	5.1	13.2
BRA 051501 (PE 011)	66.7	13.1	5.3	64.8	399.4	1.33	55.3	1.21	82.9	13.6	46.3	5.5	14.8
BRA 052051 (SE 32)	67.1	13.3	5.7	65.5	334.6	1.33	52.7	1.32	78.5	15.3	41.6	4.9	15.3
URZM 13061	67.1	13.6	5.4	62.4	239.7	1.35	50.1	1.17	74.7	13.4	43.1	4.4	16.8
URZM 13010	67.6	12.7	5.5	58.4	282.2	1.28	57.1	0.58	84.5	12.9	48.0	6.3	13.3
URZM 13088	67.8	13.1	5.1	64.9	282.9	1.34	52.4	0.70	77.2	15.6	42.9	3.7	15.8
URZM 13085	67.4	13.3	5.0	66.0	298.7	1.35	54.8	1.36	81.3	15.4	47.7	3.4	15.6
URZM 05071	67.3	13.6	5.3	63.8	295.4	1.34	53.2	0.83	79.0	19.9	29.3	3.3	16.0
URZM 11002	67.6	12.4	5.7	59.1	272.6	1.29	57.1	0.81	84.5	11.4	49.9	5.6	14.1
URZM 10001	67.6	12.9	5.6	58.5	288.3	1.28	57.5	0.70	85.0	11.6	51.9	6.6	12.8
British Virgin Islands 103	68.3	12.5	5.3	65.3	288.1	1.35	55.8	0.93	81.7	16.3	38.0	3.9	12.9
LSD[b]	0.25	0.01	0.7	0.4	18.9	0.003	2.5	0.45	3.1	1.9	2.6	0.8	1.2

TABLE III

Comparison of Compositional, Physical, and Wet-Milling Properties of GEM Accessions, Commercial Dent Hybrids, and Corn-Belt Inbreds[a]

	Compositional			Physical			Wet-Milling						
	Str (%db)	Pro (%db)	Fat (%db)	TWt (lb/bu)	KnWt (g)	ADen (g/cc)	StrY (%db)	PiS (%db)	SRec (%)	Glu (%db)	PiG (%db)	Germ (%db)	Fib (%db)
GEM accessions													
Maximum	69.1	14.4	6.2	68.2	399.4	1.37	61.9	2.03	92.9	20.1	51.9	9.5	19.3
Minimum	65.9	12.0	3.9	52.4	239.7	1.17	47.8	0.45	71.3	11.2	29.3	3.1	10.6
Mean	67.7	13.0	5.2	63.4	308.5	1.32	54.3	1.05	80.1	14.9	42.4	5.0	14.6
Commercial hybrids													
Pioneer 3394	73.3	7.7	3.4	63.3	345.4	1.26	66.9	0.25	91.3	7.15	44.6	4.0	10.7
Pioneer 3489	71.1	8.6	4.3	63.2	357.4	1.27	62.6	0.29	88.0	10.1	44.4	5.2	12.7
Corn-Belt inbreds													
B73	69.7	11.9	4.3	63.6	360.3	1.29	62.35	0.53	89.5	11.4	52.4	5.1	11.4
Mo17	68.0	14.1	3.8	60.9	205.1	1.29	58.1	1.45	85.4	13.4	47.0	6.8	12.5

[a] Str = Starch content, Pro = Protein content, Fat = Crude free fat content, TWt = Test weight, KnWt = 1000 kernel weight, ADen = Absolute density, StrY = Starch yield, PiS = Protein in starch, SRec = Starch recovery, Glu = Gluten, PiG = Protein in gluten, and Fib = Fiber yield.

TABLE IV
Correlation Coefficients Between Compositional and Physical Factors and Yields of Wet-Milled Products Based on 49 GEM Accessions[a]

	Compositional			Physical		
	Str	Pro	Fat	ADen	KnWt	TWt
Product yield (%db)						
Starch	0.424***	-0.547***	-0.328***	-0.657***	0.213**	-0.522***
Gluten	-0.312***	0.377***	0.181	0.507***	-0.239**	0.416***
Fiber	-0.253**	0.142	0.130	0.310***	-0.126	0.278***
Germ	0.114	-0.155	-0.068	-0.207*	-0.073	-0.266**
Steep liquor solids	-0.405***	0.452***	0.307***	0.612***	0.008	0.632***
Filtrate solids	0.177	-0.223**	-0.154	-0.606***	-0.213**	-0.683***
Starch recovery	0.251**	-0.456***	-0.265**	-0.657***	0.205*	-0.517***
Protein in starch	-0.282***	0.448***	0.250**	0.432***	0.008	0.431***
Protein in gluten	-0.046	-0.177	-0.146	-0.470***	0.174	-0.462***

[a] *,**,*** denote significance at 0.05, 0.01, and 0.001 probability levels, respectively. Str = Starch content, Pro = Protein content , Fat = Crude free fat content, ADen = Absolute density, KnWt = 1000 kernel weight, and TWt = Test weight.

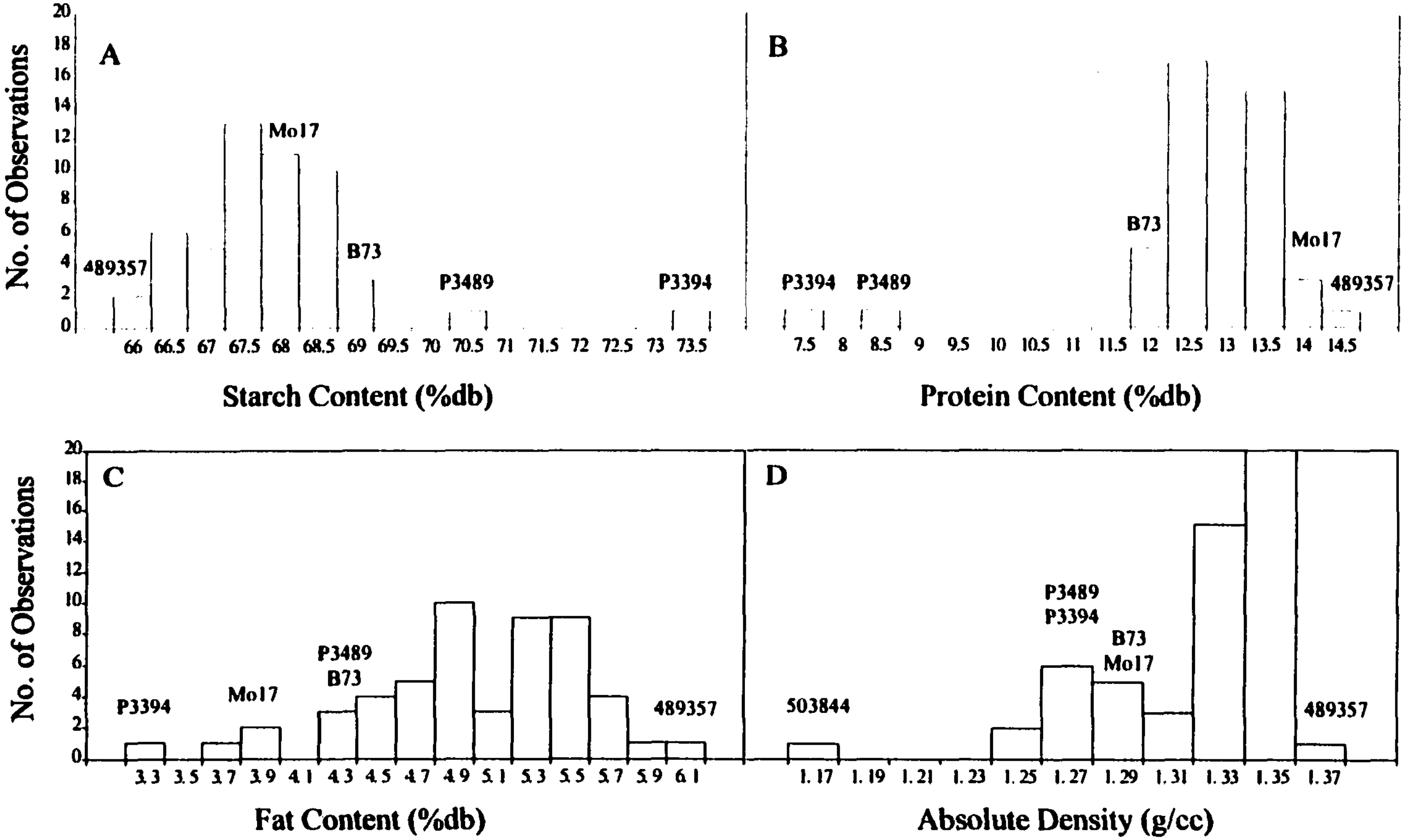

Fig. 1. Frequency distributions of compositional and physical properties of GEM accessions. Starch content (A), protein content (B), fat content (C) and absolute density (D).

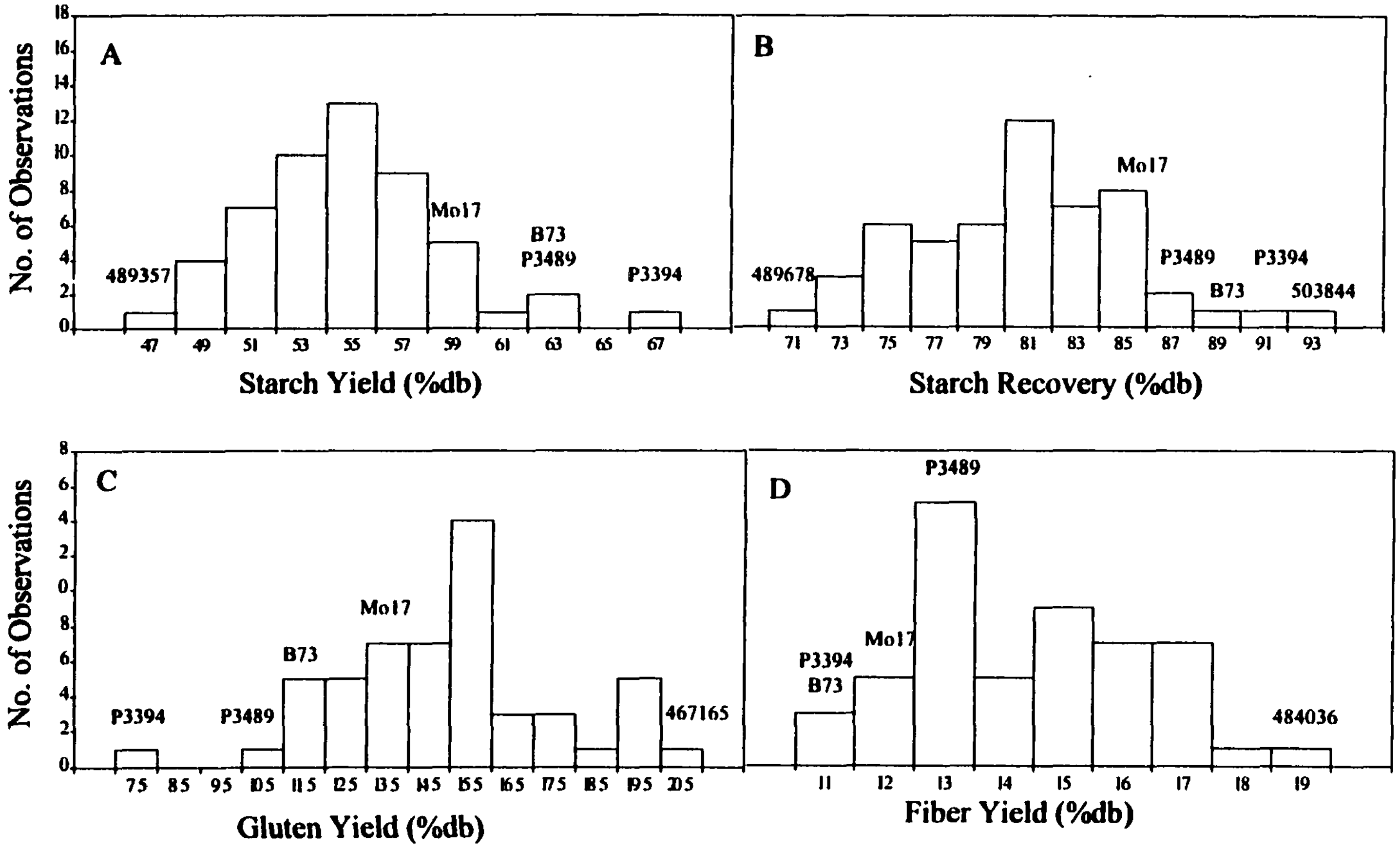

Fig. 2. Frequency distributions of wet milling properties of GEM accessions. Starch yield (A), starch recovery (B), protein yield (C), and fiber yield (D).

THERMAL, PASTING, AND GELLING PROPERTIES OF STARCHES RECOVERED FROM ACCESSIONS USED IN THE GERMPLASM ENHANCEMENT OF MAIZE PROJECT[1]

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ABSTRACT

The thermal, pasting, and gelling properties varied widely among starches recovered fromaccessions of corn that are or will be included in the Germplasm Enhancement of Maize (GEM) project. In general, the values for gelatinization, temperatures and peak height indices for starches recovered from GEM accessions were greater; but, heats of gelatinization were less for the starches recovered from the GEM

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accessions than for the starches recovered from the commercial dent corn hybrids (Pioneer 3394 and Pioneer 3489). On average, retrogradation properties were similar between populations, although there were specific GEM accessions which possessed modestly different retrogradation enthalpies. Peak viscosities, final viscosities, and viscosity breakdowns were greater for the GEM accessions starches than for the commercial hybrid starches. Pasting temperatures were about the same for all starches. Both 1-day and 7-day gel strengths were considerably greater for the starches recovered from the GEM accessions. Although differences in starch properties were statistically different, only the high gel strengths of the starches recovered from the GEM accessions were of practical significance.

INTRODUCTION

There are concerns about the narrowing genetic base of maize and about increased genetic vulnerability to changes in environmental and agronomic conditions, and new insects and disease pressure (National Academy of Sciences 1972, Brown 1975, Crossa and Gardner 1987). Exotic germplasm is of considerable interest to further improve maize and to maintain productivity in a period of changing environment and agricultural practices (Hallauer 1978, Geadlemann 1984). Exotic corn germplasm may also have valuable traits important to processing and utilization.

Limited information is available on the variability in functional properties of starches recovered from commercial maize hybrids and even less for starches recovered from exotic maize germplasm. Campbell et al (1995) used differential scanning calorimetry

(DSC) to examine a set of normal Corn-Belt dent hybrids and suggested that DSC had application in breeding programs to screen germplasm for extreme values and for developing breeding lines with unusual starch properties through crossing and recurrent selection. White et al (1990) studied intra- and inter-population variability in thermal properties of starch from normal corn populations and found significant differences among plants of the same population as well as differences between populations. In a similar study, Pollak and White (1997) compared a small group of exotic maize inbred lines and their crosses obtained from Argentina, Uruguay, and South Africa with Corn-Belt inbreds and their crosses, and found that the Corn-Belt inbreds varied more in gelatinization properties but less in retrogradation properties. Li et al (1994) also observed wide variation in starch properties of several tropical and semi-tropical corn populations. These differences, while statistically significant were not of practical significance to starch users.

Germplasm Enhancement of Maize Project (GEM) is a unique cooperation of the public and private sectors, which has initiated efforts to strengthen U.S. corn hybrids for increased yields, agronomic characteristics, and value-added traits (Pollak and Salhuana 1998). GEM is the successor to the Latin American Maize Project (LAMP) (Salhuana et al 1998) which was launched in 1987 by the U.S. Department of Agriculture, Agriculture Research Services (USDA/ARS) and 12 Latin American countries with funding from Pioneer Hi-Bred International (Johnston, IA). The primary goal of LAMP was to evaluate and maintain the irreplaceable corn germplasm bank of 12 Latin American countries and the United States.

LAMP evaluated 12,000 accessions grown at 70 locations in the United States and Latin America. Screening was done on the basis of yield potential and agronomic characteristics. Two hundred sixty-eight of these accessions were selected as potential source of high yields, and 51 chosen to initiate GEM. The objective of the present study was to screen 49 accessions (already selected on the basis of yield potential and agronomic characteristics) for thermal, pasting, and gelling properties of starch, and to select accessions with unique properties to develop value-added traits. A companion paper examined compositional, physical, and wet-milling properties of the grain from the same 49 GEM accessions is published separately (Singh et al 2000).

MATERIALS AND METHODS

Corn Samples

Forty-five Latin American and U.S. accessions were evaluated in this study (Table I). Five of the 51 original GEM accessions were not included in the study because of insufficient seed supply. Substitutions were made with four accessions from the top 5% selected LAMP accessions from Peru Lima 13, Lambayeque 46, Piura 196, and San Martin 116, which will be part of GEM in the future. The accessions (grown at North Central Regional Plant Introduction Station, Ames IA), two commercial yellow dent corn hybrids (Pioneer Brand Hybrids 3394 and 3489 from Pioneer Hi-Bred International, Inc., grown at Johnston, IA), and two public Corn-Belt inbreds, B73 and Mo17 (grown at Department of Agronomy farm, Iowa State University, Ames, IA) were dried to <15% moisture by circulating ambient air (20-22 °C) and cleaned by passing through a 6.35-mm round-hole U.S. standard sieve. Any remaining foreign material and broken kernels were removed by hand. Triplicate sample sets were prepared, placed into polyethylene bags, and stored at 4 °C until used.

Starch Isolation

Corn samples were wet-milled using a 100-g laboratory-scale wet-milling procedure originally developed by Eckhoff et al (1996) and modified by Singh et al (1997) to isolate the starches.

Thermal Properties of Starch

The thermal properties of starches were determined by using procedures reported by Campbell et al (1994) and a differential scanning calorimeter (DSC) equipped with a thermal analyzer data station (DSC-7, Perkin-Elmer, Norwalk, CT). Starch samples (4 mg) and water (8 mg) was weighed in aluminum pans. The pans were sealed and allowed to equilibrate for 1 hr. The pans were heated from 30 °C to 120 °C at a rate of 10 °C/min in the DSC heating chamber. This was adequate temperature to completely gelatinize the starch. Values of onset temperature (To), peak temperature (Tp), and change in enthalpy (ΔH) for gelatinization were recorded. Peak Height Index (PHI) was calculated by dividing ΔH by the range [2*(Tp-To)]. After gelatinization, sample pans were stored at 4 °C for 7 days and then heated from 30 °C to 90 °C for reterogradation analysis. Values of To, Tp, ΔH for retrogradation were determined by DSC. %Retrogradation was calculated by dividing ΔH for retrogradation by the ΔH for gelatinization.

Pasting Properties of Starch

Pasting properties of the starches were determined by using a Rapid-Visco-Analyzer

(RVA) (Model RVA 4, Newport Scientific, Warriewood, NSW, Australia), following the standard procedure (STD2) described in the Thermocline for WINDOWS: User's Manual (1995). An 8% (dwb) starch slurry with a final weight of 28 g was used. The STD2 profile involved equilibrating the slurry for 1 min. at 50 °C and increasing the temperature to 95 °C at the rate of 6 °C/min. The temperature was held at 95 °C for 5 min and then decreased to 50 °C at the rate of 6 °C/min. The temperature was held at 50 °C for 2 min. Peak Temperature (P_{temp}), Peak Viscosity (PV), Hot Paste Viscosity (HPV), Cold Paste Viscosity (CPV), Breakdown (BD), and Set Back (SB) values were recorded.

Gelling Properties of Starch

The starch pastes prepared in the RVA were poured into small aluminum canisters and stored at 4 °C to cause gelling. The textures (gel strengths) of the starch gels were determined after 1 and 7 days of storage at 4 °C using the procedure described by Wang et al (1992). Starch pastes were poured in a small aluminum dishes (27 mm, i.d. X 27 mm, h) and taped around the rim to increase the depth. After the storage period the gel sample was cut from the top to expose the fresh surface. Gel strengths were measured at five different locations of freshly exposed surface.

Statistical Analysis

An unpaired parametric, multiple comparison test (SAS 1984) was used to determine least significant differences (LSD) of properties among the accessions (3 replications) at the $P<0.05$ level. SAS procedure CORR was used to determine correlation coefficients among the properties at $P< 0.5$, $P<0.01$, and $P<0.001$ levels.

RESULTS AND DISCUSSION

Thermal Properties of GEM Starches

The properties of starches recovered from the 49 GEM accessions, two widely grown commercial dent hybrids, and two commonly used Corn-Belt inbreds are presented in the form of frequency distribution histograms, where the X axis represents the property and the Y axis represents the number of observations. The height of the column represents the number of accessions falling within the range of the property (column width).

The thermal properties of starches recovered from the GEM accessions showed large variations (Tables II and III). In general, onset gelatinization temperatures (To) of starches from the GEM accessions were greater than those of the commercial dent hybrids and the Corn-Belt inbreds (mean of 69.9 °C for the GEM accessions versus 66.4 and 68.3 °C for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively). The To values for the GEM accessions were greater than those of the exotic lines evaluated in other studies and those observed for Corn-Belt hybrids (Pollak and White 1997, Campbell et al 1995, Li et al 1994). The lowest (67.6 °C) and highest (72.0 °C) To among the GEM accessions were in starches recovered from URZM 13061 and Piura 196, respectively. Similarly, peak gelatinization temperatures (Tp) of starches recovered from the GEM accessions were greater than those of the commercial dent hybrids and the Corn-Belt inbreds (73.7 °C for the GEM accessions versus 71.3 and 71.8 °C for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively) (Fig. 1A). Larger To and Tp values might be due to compact nature of small sized starch granules (Knuston et al 1982) and higher degree of molecular order of granules (Krueger et al 1987a). To values also may have increased due to increased chain lengths of amylopectin present in the granules (Jane et al 1999).

Change in enthalpy for gelatinization (ΔH for gelatinization), the energy required to cook, of starches recovered from the GEM accessions ranged from 11.3 to 15.0 J/g, but on average were lower than for starches recovered from the two commercial dent hybrids (13.6 J/g) and greater than those of the two Corn-Belt inbreds (12.3 J/g) (Fig. 1B). The lowest (11.3 J/g) and highest (15.0 J/g) ΔH for gelatinization among the GEM accessions were in starches recovered from BRA 052051 (SE 32) and Piura 196, respectively. The mean values for the GEM accessions were higher than means observed for other exotic populations and Corn-Belt hybrids (Pollak and White 1997, Campbell et al 1995, Li et al 1994). Lower values of ΔH for gelatinization suggest that starches from GEM accessions might contain increased proportions of amylose, which lacks in native alignment of hydrogen bonds within starch molecule (McPherson and Jane 1999).

Peak height index (PHI) is the ratio of ΔH for gelatinization and the temperature range over which gelatinization occurs. PHI of GEM accessions ranged from 1.02 to 2.94 J/g/°C (Fig. 1C). The mean PHI of the GEM accessions (1.64 J/g/°C) was greater than that of the commercial dent hybrids (1.32 J/g/°C), but was about the same as that of the Corn-Belt inbreds (1.78 J/g/°C). The lowest and highest PHI among the GEM accessions were in starches recovered from 516026 and Cash, respectively. Several GEM accessions yielded starches that were much more uniform in gelatinization than have been observed previously where PHI ranged from 1.67 to 2.51 J/g/°C among the exotic lines and 1.25 to 2.09 J/g/°C among the Corn-Belt lines (Pollak and White 1997). Larger values of PHI can be attributed to smaller but more uniform starch granule size, leading to greater ΔH for gelatinization and smaller gelatinization range.

Onset retrogradation temperatures (To) for starches recovered from the GEM accessions ranged from 43.3 to 48.3 °C versus 43.9 and 44.7 °C for the means of the two commercial dent hybrids and the two Corn-Belt inbreds, respectively. The highest and lowest retrogradation To values among the GEM accessions were starches recovered from URZM 01089 and FS8B(T), respectively. Several GEM accessions had retrogradation To values higher (1.7 °C) than previously observed for exotic lines (Pollak and White 1997). The mean peak retrogradation temperatures (Tp) of starches recovered from the GEM accessions were similar to those of the commercial hybrids and Corn-Belt inbreds (53.8 °C versus 53.2 and 53.8 °C for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively).

Change in enthalpies (ΔH) for retrogradation for starches recovered from the GEM accessions ranged from 4.56 to 7.17 J/g versus means of 6.0 and 5.42 J/g for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively. The lowest and highest ΔH values for retrogradation among the GEM accessions were for starches recovered from Lima 13 and Dominican Republic 269, respectively.

The percentages of retrogradation (% Retro), which is the percentage ratio of ΔH for retrogradation to ΔH for gelatinization, for the GEM accessions varied widely and had a slightly greater mean value than for the commercial hybrids and the Corn-Belt inbreds (45.6% versus 44.3 and 43.8% for the two commercial dent hybrids and two Corn-Belt inbreds, respectively) (Fig. 1D). The % Retro values for some of the GEM accessions were lower than previously reported by Pollak and White (1997) for exotic lines (Pollak and White 1997, Li et al 1994) and for commercial hybrids (Campbell et al 1995). The lowest and highest % Retro values among the GEM accessions were for starches recovered from Lima 13 and URZM 01089, respectively. Increased tendency of retrogration suggests increased proportion of amylose contents and/or length of (Kasemsuwan et al 1995).

Pasting Properties of Starch

The pasting properties of GEM the starches also varied widely (Tables IV and V). Pasting temperatures (P_{temp}) of starches recovered from the GEM accessions were similar for all starches (mean of 75.0 °C for the GEM starches versus 73.5 and 79.1 °C for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively) (Fig. 2A). The lowest (72.4 °C) and highest (78.6 °C) P_{temp} values among starches recovered from the GEM accessions were ARZM 03056 and URZM 13061, respectively. Starches isolated from the GEM accessions had lower P_{temp} values than starches recovered from other inbred lines (Wang et al 1993, Campbell et al 1995).

Peak viscosities (PV) of GEM accession starches ranged 97 - 248 RVU. The mean PV of the GEM accession starches was considerably greater than that of the commercial dent hybrids and the Corn-Belt inbreds (179 RVU versus 161 and 110 RVU for the two commercial dent hybrids and two Corn-Belt inbreds, respectively) (Fig. 2B). The lowest and highest PV values among the GEM accessions were for starches recovered from URZM 13061 and ARZM 01150, respectively. Some GEM accessions had quite high PV values. Higher PV valuesis attributed to increased proportions of amylopectin in starches, which may relate to greater swelling and reduced free water (Zeng et al 1997)). Contrary to the thermal properties of starches from GEM accessions, which suggested higher levels of amylose starch, the pasting properties of starch were similar to waxy starches. Zeng et al (1997) found that harder grain produced starches with greater PV for a given amylose content. To some extent this may explain the larger values of PV for starches from GEM accessions.

Cold paste viscosity (CPV) for the GEM accession starches were generally higher (ranging 227 - 281 RVU) than for starches recovered from either the two commercial hybrids or the two Corn-Belt inbreds. The mean cold paste viscosities (CPV) of the GEM accessions were greater than that of the commercial hybrids but similar to that of the Corn-Belt inbreds (247 RVU versus 238 and 246 RVU for the two commercial dent hybrids and two Corn-Belt inbreds, respectively). Jane et al (1999) suggest that the very long chain amylopectin mimic amylose to form helical complex with lipid and intertwine with others chains to hold the integrity of starch granules during shearing and heating. After break down long chain amylopectin and amylose chain re-associate and thus increase the cold paste viscosity._

Breakdown (BD) values for starch pastes of the GEM accessions were much greater than those of either the commercial hybrids or the Corn-Belt inbreds. BD values ranged from 75 to 113 RVU compared to mean values of 82 and 86 RVU for the commercial dent hybrids and the Corn-Belt inbreds, respectively) (Fig. 2C). The lowest and highest BD values were observed in starches recovered from URZM 13061 and ARZM 01150, respectively. Lower amylose content contributes to high swelling and thus lower breakdown values (Jane 1999). The more swollen the starch granule, the more sensitive the starch paste is. Larger values of GEM starches suggest greater proportions of amylopectin.

In general, setback (SB) values for starch pastes of the GEM accessions were greater than for either the commercial hybrids or the Corn-Belt inbreds. SB values for starches recovered from GEM accessions ranged 98 - 238 RVU versus mean values of 159 and 221 RVU for the commercial dent hybrids and the Corn-Belt inbreds, respectively (Fig. 2D). The lowest and highest SB values were for starches recovered from ARZM 03056 and ARZM 16021, respectively. Long chain amylopectin and amylose contribute to SB (Zeng et al 1997).

Gelling Properties of Starch

In general, 1-day gel strengths for starches recovered from GEM accessions were greater than those of the commercial hybrids and the Corn-Belt inbreds. The 1-day gel strengths of starches recovered from the GEM accessions ranged from 9.5 to 21.0 g versus means of 13.2 and 9.6 g, for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively (Fig. 3A). The lowest and highest gel strengths (1 day) were observed in starches recovered from Cuba 110 and BRA 052051 (SE 32), respectively.

The 7-day gel strengths of the starches recovered from the GEM accessions were also considerably higher than for starches recovered from the commercial hybrids and the Corn-Belt inbreds. The 7-day gel strengths ranged from 23.9 to 66.2 g versus means of 24.9 and 20.2 g for the two commercial dent hybrids and the two Corn-Belt inbreds, respectively) (Fig. 3B). The lowest and highest 7-day gel strengths were observed in starches recovered from URZM 13061 and FS8A(T), respectively. Larger values of gel strengths could be due to larger proportions of long chain amylopectin and amylose.

Single Factor Correlation

Table VI shows correlation coefficients between the thermal, pasting, and gelling properties of the starches from the 49 GEM accessions. PV and HPV were positively correlated with To, Tp, and ΔH for gelatinization, retrogradation Tp, and PHI. Retrogradation To was negatively correlated with PV but positively correlated with HPV. CPV was negatively correlated with ΔH for gelatinization. P_{temp} was negatively correlated with gelatinization To, PHI, and retrogradation To and Tp.

One might expect P_{temp} and gelatinization Tp to be strongly and positively correlated. However, gelatinization of starch is affected by the size of the granule, whereas the development of viscosity is largely due to the amylose and lipid contents present in the starch. Since the basic mechanism and constituents involved in the two events are different, their peak temperatures are also independent of each other. However, P_{temp} is always greater than Peak gelatinization temperature. BD was strongly and negatively correlated with gelatinization To and Tp but weakly and negatively correlated with ΔH for gelatinization. SB was negatively correlated with To and ΔH for gelatinization, but weakly and negatively correlated with gelatinization Tp, PHI and retrogradation To and Tp. Gel strength after 1 day of storage was positively correlated with gelatinization Tp. Gel strength after 7 days of storage was strongly and positively correlated with gelatinization To and Tp, and weakly and positively correlated with retrogradation Tp.

CONCLUSIONS

Starches isolated from the GEM accessions possessed statistically different thermal and pasting properties from commercial hybrids and common Corn-Belt hybrids. These differences were too small to be of practical significance to starch users. However, recurrent selection using selected GEM accessions may lead to hybrids possessing unique and possibly valuable properties. The gel strengths of the starches isolated from the GEM accessions were considerably greater and may have practical implications. The large genetic variation among the thermal, pasting, and gelling properties of starches recovered from the GEM accessions may be useful in developing hybrids with novel starches. While a number of thermal properties were correlated at low rejection levels with pasting and gelling properties, the correlations were not such that pasting and gelling properties could be predicted from DSC thermal properties.

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TABLE I
Description of 49 GEM Accessions

Accession names	PI	Race	Kernel Color/Type	Area of Adaptation	Source
Cash	278710	Corn-Belt Dent	Yellow Dent	Temperate	USA, Ohio
Golden Queen	452040	Corn-Belt Dent	Yellow Dent	Temperate	USA, Ohio
Big White	452054	Southern Dent	White Dent	Temperate	USA, Tennessee
CHZM 04030	467139	Camelia	Orange Flint	Temperate	Chili, Coquimbo
CHZM 05015	467165	Camelia	Orange Flint	Temperate	Chili, Valparaiso
URZM 01089	479145	Cateto Sulino	Orange Flint	Temperate	Uruguay
Cuba 117	483816	Argentino	Orange Flint	Tropical	Cuba
Dominican Republic 150	484028	Mixed	Yellow Semident	Tropical	Dominican Republic
St. Croix 1	484036	St. Croix	Yellow Semident	Tropical	Virgin Islands (US)
Antigua 3	484991	Criollo	Yellow Semident	Tropical	Antigua & Barbuda
Lima 13	485347	Perla	Orange Flint	Tropical	Peru, Lima
Cuba 110	489357	Argentino	Orange Flint	Tropical	Cuba
Cuba 164	489361	Mixed	Orange Semiflint	Tropical	Cuba
Dominican Republic 269	489678	Canilla	Yellow Semident	Tropical	Dominican Republic
ARZM 01150	491741	Dent. Blanco Rugoso	White Dent	Temperate	Argentina, Buenos Aires
ARZM 03056	491799	Dentado Blanco	White Dent	Temperate	Argentina, Entre Rios
ARZM 13026	492746	Cristalino Colorado	Orange Flint	Temperate	Argentina, La Rioja
ARZM 13035	492753	Cristalino Colorado	Orange Flint	Temperate	Argentina, La Rioja
ARZM 17026	493012	Cristalino Colorado	Orange Flint	Temperate	Argentina, San Luis
ARZM 17056	493039	Cristalino Colorado	Orange Flint	Temperate	Argentina, San Luis
Guadelupe 5	498569	Early Caribbean	Yellow Flint	Tropical	Guadeloupe
Guatemala 209	498583	Tuson	Yellow Flint	Tropical	Guatemala
Lambayeque 46	503732	Arizona	White Dent	Tropical	Peru, Lima
Piura 196	503844	Alazan	Red/White cap flour	Tropical	Peru, Lima
Barbados Group 2	503885	Tuson	Yellow Dent	Tropical	Barbados
Puerto Rico Group 3	504142	Mixed	Yellow Dent	Tropical	Puerto Rico
St. Croix Group 3	504148	Tuson	Yellow Dent	Tropical	Virgin Islands (US)

Table I. (Continued)

Accession name	PI	Race	Kernel Color/Type	Area of Adaptation	Source
San Martin 116	515097	Cuban	Yellow Flint	Tropical	Peru, San Martin
ARZM 16021	516022	Cristalino Colorado	Orange Flint	Temperate	Argentina, Mendoza
ARZM 16026	516027	Cristalino Colorado	Orange Flint	Temperate	Argentina, Mendoza
ARZM 16035	516036	Cristalino Colorado	Orange Flint	Temperate	Argentina, Mendoza
FS8A(S)	536619	Mixed	Yellow Semident	Temperate	US, Florida
FS8A(T)	536620	Mixed	Yellow Semident	Temperate	US, Florida
FS8B(S)	536621	Mixed	Yellow Semident	Temperate	US, Florida
FS8B(T)	536622	Mixed	Yellow Semident	Temperate	US, Florida
Pasco 14	571679	Unclassified	Yellow Dent	Tropical	Peru, Pasco
Chiapas 462	583888	Hybrido Blanco	White Dent	Tropical	Mexico, Chiapas
British Virgin Islands 155	583901	Tuson	Yellow Dent	Tropical	Virgin Islands (British)
BRA 051403 (PE 01)	583911	Cateto	Orange Flint	Tropical	Brazil, Pernambuco
BRA 051501 (PE 011)	583912	Unclassified	Yellow Dent	Tropical	Brazil, Pernambuco
BRA 052051 (SE 32)	583917	Dente Amarelo	Yellow Dent	Tropical	Brazil, Sergipe
URZM 13061	583922	Cateto Sulino	Orange Flint	Temperate	Uruguay
URZM 13010	583923	Dente Branco	Orange Dent	Temperate	Uruguay
URZM 13088	583925	Cateto Sulino	Orange Flint	Temperate	Uruguay
URZM 13085	583927	Cateto Sulino	Orange Flint	Temperate	Uruguay
URZM 05071	583937	Riograndense	Orange Semident	Temperate	Uruguay
URZM 11002	583938	Dente Branco	White Dent	Temperate	Uruguay
URZM 10001	583942	Dente Branco	White Dent	Temperate	Uruguay
British Virgin Islands 103	586761	Criollo	Yellow Semiflint	Tropical	Virgin Islands (British)

TABLE II
Thermal Properties of Starches Recovered from GEM Accessions[a]

Accession names	Gelatinization				Retrogradation			
	To (°C)	Tp (°C)	ΔH (J/g)	PHI (J/g*°C)	To (°C)	Tp (°C)	ΔH (J/g)	% Retro (%)
Cash	71.1	73.5	12.3	2.94	46.4	55.5	5.71	46.4
Golden Queen	69.3	73.8	12.6	1.40	44.9	53.7	5.63	44.8
Big White	70.1	73.0	14.5	2.19	46.4	54.6	6.05	41.8
CHZM 04030	70.1	74.0	13.0	1.66	44.2	52.8	6.11	46.9
CHZM 05015	70.7	74.3	13.7	1.85	44.7	53.9	6.28	46.0
URZM 01089	70.3	73.8	11.9	1.67	43.3	52.0	6.53	54.9
Cuba 117	69.5	73.3	13.9	1.82	43.9	53.8	6.88	49.7
Dominican Republic 150	67.9	71.9	11.5	1.44	44.3	53.2	5.31	46.3
St. Croix 1	69.5	73.3	14.4	1.88	45.3	54.0	6.59	45.9
Antigua 3	70.9	74.1	12.7	2.06	44.6	53.7	6.19	48.8
Lima 13	68.7	72.6	12.9	1.65	44.9	52.9	4.56	35.4
Cuba 110	70.4	74.1	13.5	1.85	44.5	53.8	6.63	49.1
Cuba 164	70.8	73.5	14.6	2.27	44.9	54.3	6.77	46.3
Dominican Republic 269	70.5	74.0	14.8	1.88	45.1	54.5	7.17	48.4
ARZM 01150	71.8	74.0	12.9	1.97	46.8	55.8	6.06	47.0
ARZM 03056	71.6	72.1	13.2	2.16	44.0	53.1	6.05	45.8
ARZM 13026	69.3	73.4	13.4	1.66	44.6	53.3	6.53	48.9
ARZM 13035	69.2	74.2	12.1	1.21	44.6	53.6	4.45	45.1
ARZM 17026	69.8	73.7	12.1	1.57	44.3	53.3	5.70	47.3
ARZM 17056	70.5	74.7	12.5	1.48	44.3	53.3	6.58	52.9
Guadelupe 5	69.7	73.3	12.4	1.69	46.5	55.3	5.91	47.8
Guatemala 209	69.6	73.6	12.7	1.60	44.0	52.8	6.01	47.4
Lambayeque 46	71.2	74.6	12.8	1.89	44.3	52.8	5.83	45.5
Piura 196	72.0	75.3	15.0	2.26	43.5	53.5	6.89	46.0

[a] To = Onset temperature, Tp = Peak temperature, ΔH = Change in enthalpy, PHI = Peak height index, and % Retro = % Retrogradation.

[b] Least significant difference ($P < 0.05$).

Table II. (Continued)

Accession names	Gelatinization				Retrogradation			
	To (°C)	Tp (°C)	ΔH (J/g)	PHI (J/g*°C)	To (°C)	Tp (°C)	ΔH (J/g)	% Retro (%)
Barbados Group 2	70.9	73.6	12.9	1.84	44.2	53.6	5.78	44.7
Puerto Rico Group 3	69.9	73.4	13.0	1.87	43.7	52.7	5.49	42.6
St. Croix Group 3	70.2	73.2	13.0	1.76	44.4	53.6	5.58	42.9
San Martin 116	69.5	74.3	13.8	1.03	43.3	52.8	6.50	47.1
ARZM 16021	68.7	74.4	12.3	1.08	43.3	52.9	5.66	46.1
ARZM 16026	69.8	75.0	13.1	1.25	43.3	54.5	6.19	47.4
ARZM 16035	68.3	73.9	11.8	1.02	44.5	53.6	4.82	40.8
FS8A(S)	70.3	74.8	12.2	1.35	45.2	53.8	5.08	41.6
FS8A(T)	71.5	73.9	12.8	1.55	47.2	56.3	5.73	44.9
FS8B(S)	70.8	74.7	12.3	1.55	44.8	55.4	5.97	48.7
FS8B(T)	70.0	73.2	12.1	1.88	48.3	57.2	4.90	40.6
Pasco 14	70.2	73.8	12.6	1.79	45.1	54.5	5.62	44.6
Chiapas 462	70.4	74.5	12.7	1.55	43.7	52.7	5.64	44.5
British Virgin Island 155	69.8	73.3	12.3	1.75	44.9	54.1	5.55	45.1
BRA 051403 (PE 01)	70.7	74.2	12.8	1.83	44.1	53.2	5.55	43.4
BRA 051501 (PE 011)	70.0	73.7	12.2	1.67	48.0	56.4	5.14	42.0
BRA 052051 (SE 32)	71.2	73.3	11.3	1.57	46.3	54.1	5.42	48.1
URZM 13061	67.6	73.2	11.7	1.05	43.5	52.7	5.28	45.0
URZM 13010	67.7	73.1	12.5	1.15	44.7	53.1	5.0	40.0
URZM 13088	68.8	73.7	11.3	1.16	43.7	52.7	5.24	50.0
URZM 13085	69.1	73.2	12.0	1.26	43.8	52.9	5.98	44.0
URZM 05071	69.0	73.9	14.1	1.44	45.7	54.6	5.83	42.5
URZM 11002	68.8	73.0	12.8	1.58	44.6	52.8	4.70	45.4
URZM 10001	69.0	73.2	12.1	1.46	46.2	54.7	6.04	38.9
British Virgin Island 103	69.0	72.6	11.8	1.75	43.9	53.6	6.04	51.1
LSD[b]	0.6	0.5	0.46	0.29	1.0	0.9	0.42	3.2

TABLE III

Comparison of Thermal Properties of Starches Recovered from GEM Accessions, Commercial Dent Hybrids, and Corn-Belt Inbreds[a]

Accession names	Gelatinization				Retrogradation			
	To (°C)	Tp (°C)	ΔH (J/g)	PHI (J/g*°C)	To (°C)	Tp (°C)	ΔH (J/g)	% Retro (%)
GEM accessions								
Maximum	72.0	75.3	15.0	2.94	48.3	57.2	7.17	54.9
Minimum	67.6	71.9	11.3	1.02	43.3	52.0	4.56	35.4
Mean	69.9	73.7	12.8	1.64	44.8	53.8	5.81	45.6
Commercial hybrids								
Pioneer 3394	64.8	70.6	13.5	1.15	43.3	52.7	6.09	45.2
Pioneer 3489	67.3	71.9	13.7	1.49	44.5	53.6	5.90	43.2
Common inbreds								
B73	67.1	70.8	11.8	1.57	45.2	54.7	5.12	43.4
Mo17	69.4	72.7	12.8	1.98	44.2	52.8	5.71	44.2

[a] To = Onset temperature, Tp = Peak temperature, ΔH = Change in enthalpy, PHI = Peak height index, and % Retro = % Retrogradation.

TABLE IV
Pasting and Gelling Properties of Starches Recovered from GEM Accessions[a]

Accession Names	Pasting Properties						Gel Strength	
	PV (RVU)	HPV (RVU)	CPV (RVU)	Tp (°C)	BD (RVU)	SB (RVU)	1 day (g)	7 days (g)
Cash	145	46	266	76	99	220	12.7	30.4
Golden Queen	194	97	239	75	97	142	13.6	40.1
Big White	214	121	244	73	94	123	14.0	35.2
CHZM 04030	127	29	243	78	98	214	12.4	32.0
CHZM 05015	135	30	243	78	105	213	12.0	32.4
URZM 01089	177	65	259	75	113	195	13.7	36.8
Cuba 117	142	44	237	76	98	194	11.1	31.9
Dominican Republic 150	187	83	233	73	104	150	15.3	42.5
St. Croix 1	223	118	246	74	105	128	15.9	50.1
Antigua 3	215	119	281	73	96	162	16.1	50.9
Lima 13	71	61	278	75	111	217	13.9	36.9
Cuba 110	118	26	246	78	92	220	9.5	29.8
Cuba 164	225	113	241	74	112	129	12.4	52.3
Dominican Republic 269	193	93	245	74	100	152	14.2	42.7
ARZM 01150	249	136	242	74	113	106	11.9	45.4
ARZM 03056	234	129	227	72	105	98	13.4	36.5
ARZM 13026	139	38	248	77	102	210	12.2	36.0
ARZM 13035	141	39	240	77	101	201	11.7	37.5
ARZM 17026	158	56	256	76	103	200	11.9	39.2
ARZM 17056	135	39	239	77	95	200	13.0	31.8
Guadelupe 5	141	40	237	79	101	197	15.2	43.3
Guatemala 209	176	71	248	76	104	176	14.9	61.0
Lambayeque 46	194	85	257	76	109	172	15.7	50.8

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[a] PV = Peak viscosity, HPV = Hot paste viscosity, CPV = Cold paste viscosity, Tp = Pasting temperature, BD = Breakdown (PV-HPV), SB = Setback (CPV-HPV), 1 day and 7 days = Gel strength after 1 and 7 days of storage at 4°C, respectively.

[b] Least significant difference ($P < 0.05$).

Table IV. (Continued)

	Pasting Properties						Gel Strength	
Accession Names	PV (RVU)	HPV (RVU)	CPV (RVU)	Tp (°C)	BD (RVU)	SB (RVU)	1 day (g)	7 days (g)
Piura 196	163	75	246	76	87	170	14.2	40.4
Barbados Group 2	180	91	230	74	90	140	15.4	46.0
Puerto Rico Group 3	186	103	234	74	83	130	13.7	51.7
St. Croix Group 3	216	126	250	74	90	124	17.4	58.5
San Martin 116	169	72	244	76	98	172	16.0	38.6
ARZM 16021	124	32	269	78	92	238	14.6	38.4
ARZM 16026	202	92	272	76	110	180	16.6	63.6
ARZM 16035	182	82	241	74	100	159	15.1	34.3
FS8A(S)	201	109	263	75	92	154	18.8	54.7
FS8A(T)	210	125	264	74	85	139	19.2	66.2
FS8B(S)	207	111	244	75	96	133	15.4	65.4
FS8B(T)	159	66	246	75	93	180	12.4	25.2
Pasco 14	216	119	232	74	97	113	17.9	46.8
Chiapas 462	206	124	244	74	82	120	14.5	45.6
British Virgin Island 155	204	103	243	74	101	140	16.1	49.5
BRA 051403 (PE 01)	179	92	233	75	87	141	16.5	45.9
BRA 051501 (PE 011)	190	91	246	74	99	155	18.8	49.3
BRA 052051 (SE 32)	217	126	243	74	90	117	21.0	51.5
URZM 13061	98	23	242	79	75	219	10.7	23.9
URZM 13010	161	63	250	75	97	187	11.4	25.0
URZM 13088	161	62	242	76	99	180	14.1	32.8
URZM 13085	176	75	240	75	101	164	15.7	36.5
URZM 05071	165	66	244	73	99	178	13.4	29.1
URZM 11002	161	67	244	75	94	177	11.3	27.3
URZM 10001	160	64	244	75	95	179	11.3	27.0
British Virgin Island 103	224	125	240	73	99	115	18.3	4.5
LSD[b]	9	6	8	2	9	9	1.0	3.2

TABLE V
Comparison of Pasting and Gel Properties of Starches Recovered from GEM Accessions, Commercial Dent Hybrids, and Corn-Belt Inbreds[a]

	Pasting Properties						Gel Strength	
	PV (RVU)	HPV (RVU)	CPV (RVU)	Tp (°C)	BD (RVU)	SB (RVU)	1 day (g)	7 days (g)
GEM accessions								
Maximum	249	136	281	79	113	238	21.0	66.2
Minimum	98	23	227	72	75	98	9.5	23.9
Mean	179	81	247	75	97	168	14.4	41.7
Commercial hybrids								
Pioneer 3394	183	97	235	73	86	138	12.9	23.5
Pioneer 3489	140	61	240	74	79	179	13.4	26.2
Common inbreds								
B73	101	17	277	80	84	260	10.0	17.0
Mo17	120	32	214	78	88	182	9.2	23.3

[a] PV = Peak viscosity, HPV = Hot paste viscosity, CPV = Cold paste viscosity, Tp = Pasting temperature, BD = Breakdown (PV-HPV), SB = Setback (CPV-HPV), and 1 day and 7 days = Gel strength after 1 and 7 days of storage at 4°C, respectively.

TABLE VI

Correlation Coefficients Between Thermal Properties and Pasting and Gelling Properties of Starches Recovered from 49 GEM Accessions

Thermal Properties[b]	Pasting Properties[c]						Gel Strength[d]	
	PV	HPV	CPV	Tp	BD	SB	1 day	7 days
Gelatinization								
To	0.41***	0.4***	-0.01	-0.25**	-0.36***	-0.39***	0.17	0.4***
Tp	0.24**	0.26**	0.09	-0.05	-0.36***	-0.23**	0.24**	0.4***
ΔH	0.26**	0.26**	-0.17*	-0.16	-0.19*	-0.29***	-0.12	0.1
PHI	0.25**	0.22*	0.01	-0.21*	-0.01	-0.22*	-0.09	0.1
Retrogradation								
To	-0.22*	0.20*	0.04	-0.22*	-0.08	-0.18*	0.15	0.1
Tp	0.22**	0.23*	-0.01	-0.23**	-0.15	-0.22*	0.15	0.2*
ΔH	0.08	0.03	-0.13	0.07	0.02	-0.09	-0.08	0.1
% Retro	-0.05	-0.10	-0.04	0.16	0.12	0.06	-0.021	0.1

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[a] *,**,*** = Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

[b] To = Onset temperature, Tp = Peak temperature, ΔH = Change of enthalpy, PHI = Peak height index, and % Retro = % Retrogradation.

[c] PV = Peak viscosity, HPV = Hot paste viscosity, CPV = Cold paste viscosity, Tp = Pasting temperature, BD = Breakdown (PV-HPV), and SB = Setback (CPV-HPV).

[d] Gel strengths after 1 and 7 days of storage at 4 °C.

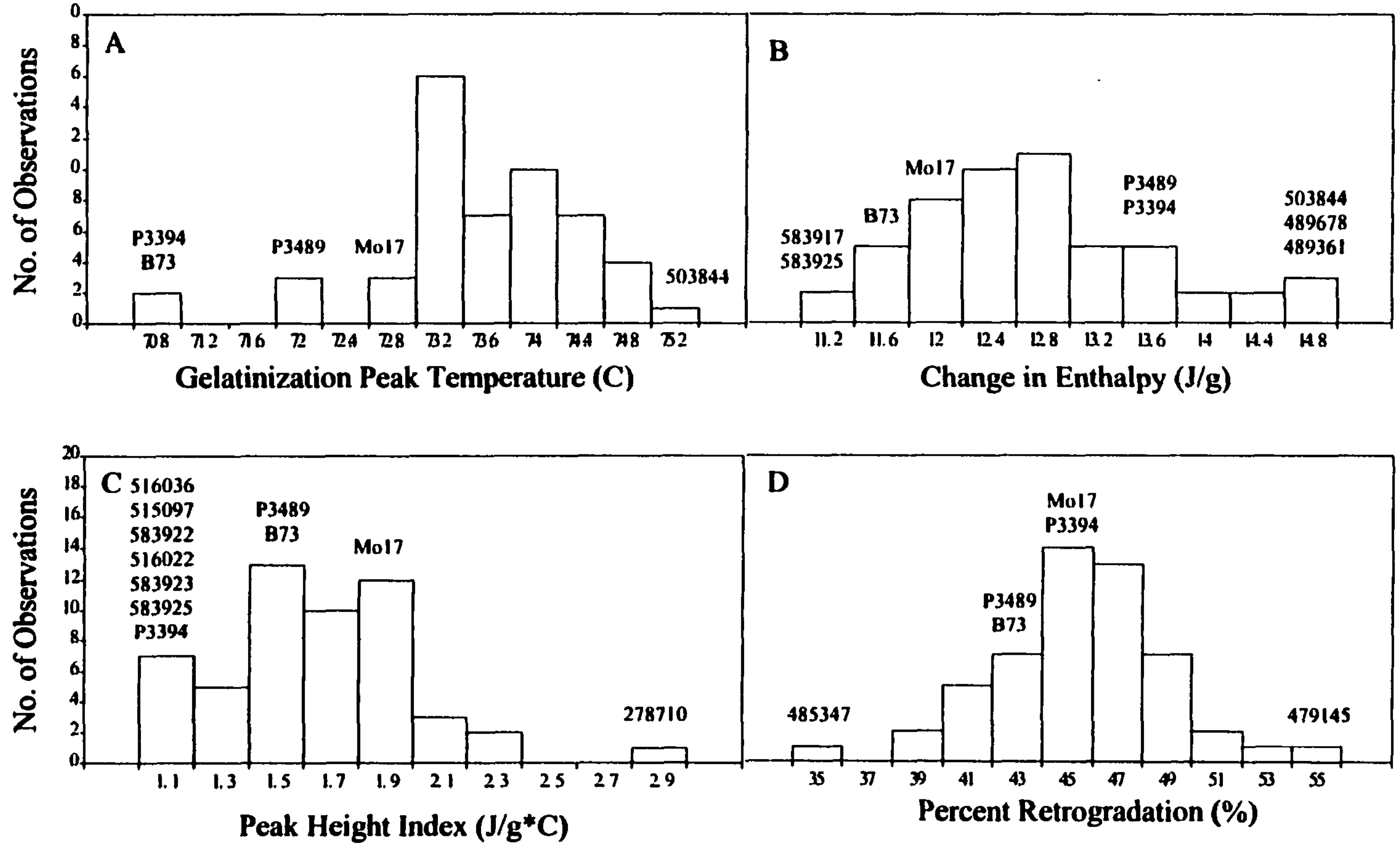

Fig. 1. Frequency distributions of thermal properties of GEM accessions. Gelatinization onset temperature (A), change in enthalpy of gelatinization (B), peak height index (C), and percent retrogradation (D).

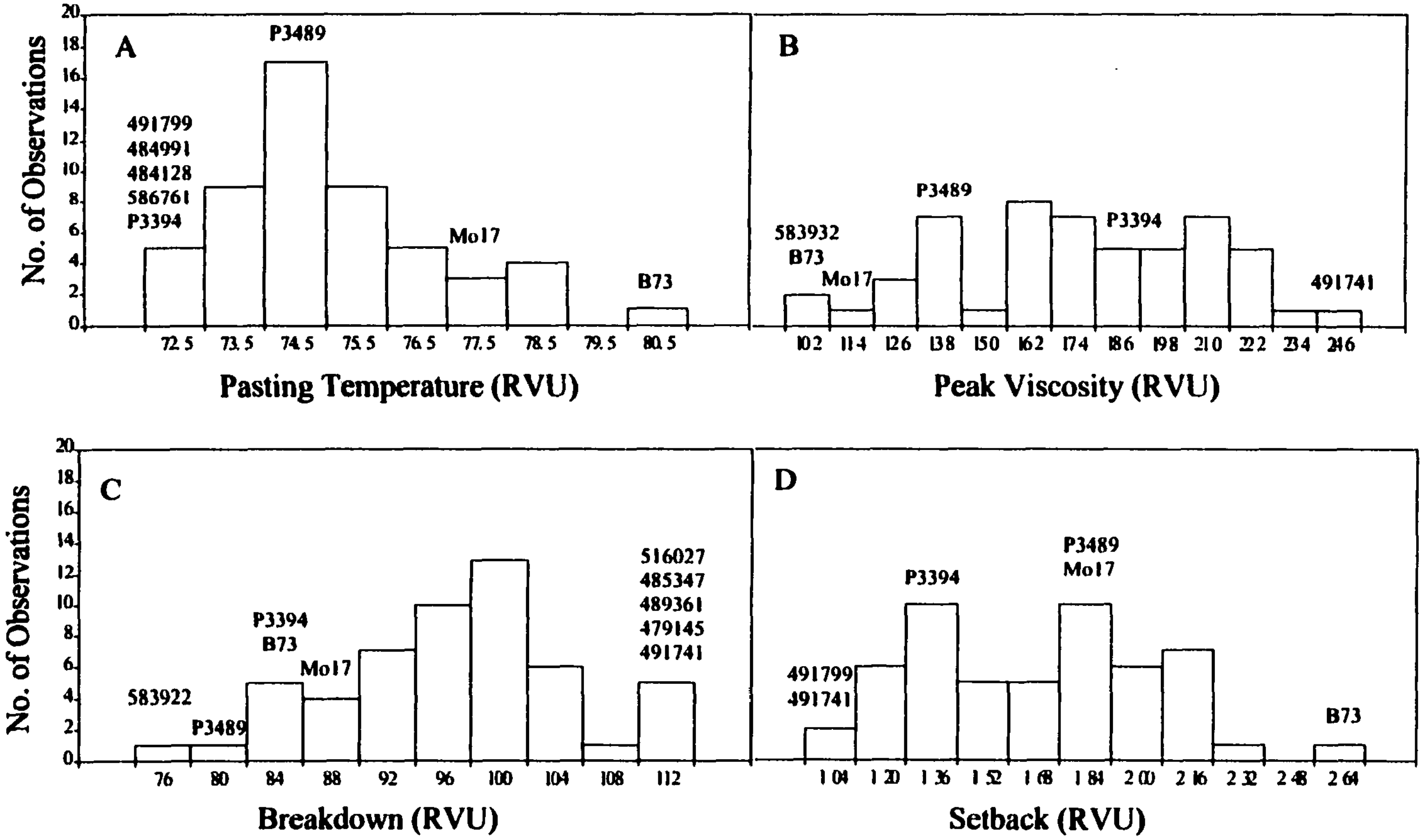

Fig. 2. Frequency distributions of pasting properties of GEM accessions. Pasting temperature (**A**), peak viscosity (**B**), breakdown (**C**), and setback (**D**).

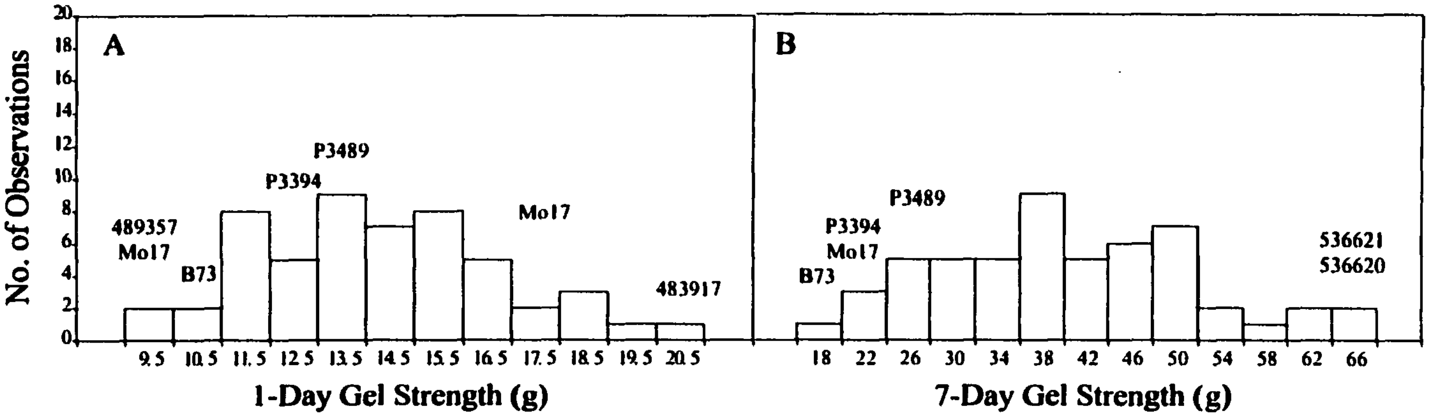

Fig. 3. Frequency distributions of gelling properties of GEM accessions. 1-day gel strength (A), 7-day gel strength (B).

HETEROSIS IN COMPOSITIONAL, PHYSICAL, AND WET-MILLING PROPERTIES OF ADAPTED X EXOTIC CORN BREEDING CROSSES[1]

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ABSTRACT

Compositional, physical, and wet-milling properties of 10 corn accessions from the Germplasm Enhancement of Maize Project (GEM), two Corn-Belt dent inbreds (B73 and Mo17), and their crosses were compared to determine heterosis among these important traits and to gain insight about their genetic control. Crossing the selected GEM accessions with each inbreds increased protein contents and reduced starch contents. Mean absolute densities and test weights of the crosses were greater than for either parent. Little heterosis was

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observed in 1000 kernel weight, and the crosses had values similar to their GEM parents (relatively low). Grain protein contents were greater for the crosses than for the GEM accessions; starch and oil contents of the crosses were intermediate to both parents. The wet-milling properties of the crosses were improved over those of the GEM accessions. Crossing the GEM accessions with B73 greatly increased residual protein contents in the recovered starch, whereas values for protein in starch for the GEM x Mo17 crosses were greater than for the GEM accessions and not unlike that of Mo17. High-parent heterosis was greater in the GEM x Mo17 crosses for absolute density, test weight, 1000 kernel weight, and starch content, but lower for protein and fat contents. GEM x Mo17 crosses yielded greater high-parent heterosis for starch yield and starch recovery, and lower high-parent heterosis for gluten and fiber yields. Mo17 expressed poor wet-milling properties as an inbred but produced superior hybrids than B73, which had better wet-milling properties as an inbred.

INTRODUCTION

Heterosis or hybrid vigor is the superiority of the hybrid progeny over the inbred parents for the trait of interest, which is usually grain yield. Both mid-parent heterosis and high-parent heterosis are used by maize breeders. Mid-parent heterosis is the deviation of progeny from the mean of the parents divided by the mean value of the parents. High-parent heterosis is the deviation of progeny from the high parent divided by the high parent.

There are no studies of heterosis in compositional and physical properties of corn, and the only study that has examined heterosis in wet-milling properties of corn has been that of Zehr et al (1995) who compared 15 Corn-Belt inbreds and 20 related hybrids. They observed significant divergence of hybrids from mid-parent values and attributed the lower germ and fiber yields, and the higher gluten and filtrate solids yields compared with the inbreds to the larger kernels of the hybrids. They also concluded that starch yield and recovery of the crosses were additive with respect to parental values. Because of its diverse background and large genetic variability for a wide variety of traits, exotic germplasm may be used to develop hybrids with improved compositional, physical, and wet-milling properties useful to grain handlers and processors.

The Germplasm Enhancement of Maize (GEM) project is a unique cooperation of the public and private sectors, which has initiated efforts to strengthen U.S. corn hybrids for increased yields, agronomic characteristics, and value-added traits (Pollak and Salhuana et al 1998). GEM is the successor to the Latin American Maize Project (LAMP) (Salhuana et al 1998) which was launched in 1987 by the U.S. Department of Agriculture, Agriculture Research Services (USDA/ARS) and 12 Latin American countries with funding from Pioneer Hi-Bred International (Johnston, IA). The principle goal of LAMP was to evaluate and maintain the irreplaceable corn germplasm bank material of 12 Latin American countries and the United States.

LAMP evaluated 12,000 accessions grown at 70 locations in the United States and Latin America. Screening was done on the basis of yield potential and agronomic characteristics. Two hundred sixty-eight of these accessions were selected as potential source of high yields, then 51 were chosen to initiate GEM.

The objective of the present study was to evaluate heterosis of compositional, physical, and wet-milling properties in selected GEM x Corn-Belt inbred crosses and to gain insight about the underlying genetic control of these traits.

MATERIALS AND METHODS

Sample Preparation

Ten GEM accessions (Table I) with high and low values for each of the traits were successively selected (on the basis of extreme property values) for crossing with two widely used public Corn-Belt dent inbreds (Mo17 and B73). The selected accessions and Corn-Belt inbreds were grown in a nursery near Pronce, Puerto Rico, during the winter of 1995-96. Each accession was crossed to both inbred lines using the inbred as a male.

Samples were cleaned by using a 6.35-mm round-hole U.S. standard sieve (Dual Mfg Co., Chicago, IL). Additional foreign material and broken kernels were removed by hand. Triplicate sample sets were prepared, placed into polyethylene bags, and stored at 4 °C until processed.

Compositional Properties of Grain

Moisture contents of the corn were determined by using AACC method 44-15A (AACC 1983). Starch, protein, and crude free fat contents (dry basis) were estimated in triplicate by using an Infratec Grain Analyzer, a near-infrared transmittance (NIR-T) analyzer (Tecator, Hoganas, Sweden).

Physical Properties of Grain

Kernel absolute densities were determined by using an AccuPyc 1330 pycnometer

(Micrometrics, Norcross, GA). Test weight was determined by using Federal Grain Inspection Services (FGIS 1988) standard methods. Thousand-kernel weight was determined by using an electronic counter (Syntron, Homer City, PA) to count kernels. Values were determined in triplicate and adjusted to a 15% moisture basis by using moisture adjustment equations developed by Dorsey-Redding et al. (1990).

Wet-milling Properties

Corn was wet milled in triplicate using a modified 100-g laboratory-scale wet-milling procedure originally developed by Eckhoff et al (1996) and modified by Singh et al (1997).

The moisture contents of the wet-milled fractions were determined according to AOAC method 14.004 (AOAC 1984) so that material balances could be determined. Protein contents were determined in duplicate according to the Corn Refiners' Association macro-Kjeldahl method A-18 (CRA 1986). Because of the limited amounts of fractions available in the modified 100-g procedure, only the starch and gluten fractions were analyzed for protein contents.

Statistical Analysis

An unpaired parametric, multiple comparison test (SAS 1984) was used to determine least significant differences (LSD) of properties among the accessions at probability levels of $P < 0.05$, 0.01, and 0.001.

RESULTS AND DISCUSSION

Compositional, physical, and wet-milling properties of the 10 selected GEM accessions and their crosses with B73 and Mo17 are shown in Tables II and III, respectively. Values for the crosses are directly compared with the parents in Figures 1 and II.

Compositional Properties

Starch contents ranged 67.2-69.9% for the GEM x B73 crosses and 66.5-70.4% for the GEM x Mo17 crosses (Fig. 1A). The mean starch content for the GEM x B73 crosses did not deviate greatly from the mean of the parents, but the mean of the GEM x Mo17 crosses was greater than the mean of the parents. The highest and lowest starch contents among the crosses were Dominican Republic 150 x Mo17 and Cuba 110 x Mo17, respectively.

The crosses contained considerably more protein than did the GEM accessions (13.7% for the GEM x B73 crosses and 13.2% for the GEM x Mo17 crosses versus 12.9% for the GEM accessions) (Fig. 1B). B73, despite having lower protein content (11.9%) than Mo17 (14.1%), produced crosses with greater protein contents than did Mo17. Greater protein content is not a desired characteristic for improving wet-milling properties, because additional protein makes the separation of all fractions more difficult. The highest and lowest grain protein contents were for Cuba 110 x Mo17 and ARZM 01150 x Mo17, respectively.

The mean oil content of the crosses did not deviate greatly from the mean of the parents (4.9% for the GEM x B73 crosses and 4.6% for the GEM x Mo17 crosses versus 5.2, 4.3 and 3.8% for the GEM accessions, B73, and Mo17, respectively) (Fig. 1C). Thus, the increased protein contents do not appear to come from greater proportions of germ. FS8A(S) x B73 had the highest (5.9%) and Piura 196 x Mo17 (3.8%) had the lowest oil contents among the crosses.

Physical Properties

Thousand kernel weights of the crosses also varied widely (234 to 371 g for the GEM x B73 crosses versus 260 to 373 g for the GEM x Mo17 crosses); but, the mean 1000 kernel weights of the crosses were similar to the mean of the GEM accessions (303 g for the GEM x Mo17and 310 g for the GEM x B73 crosses versus 304 g for the GEM accessions).

Test weights ranged 56.9-67.1 lb/bu for the GEM xB73 crosses and 61.0-67.9 lb/bu for the GEM x Mo17 crosses; but on average, test weights of the crosses were greater than either parents (64.0 lb/bu for the GEM x Mo17 crosses and 65.4 lb/bu for the GEM x B73 crosses versus 62.6, 63.6 and 60.9 lb/bu for the GEM accessions, B73, and Mo17, respectively).

Absolute densities of the crosses ranged 1.29-1.39 g/cc for the GEM x B73 crosses and 1.31-1.38 g/cc for the GEM x Mo17 crosses; but, on average, absolute densities of the crosses were higher than those of the parents (1.34 g/cc for the GEM x B73 and 1.35 g/cc for the GEM x Mo17crosses versus 1.30, 1.29, and 1.29 g/cc for the GEM accessions, B73, and Mo17, respectively) (Fig. 1C). Accessions Cuba 110 and ARZM 01150 had the highest and lowest absolute densities among the GEM x B73 crosses (1.39 g/cc for Cuba

110 x B73 and 1.29 g/cc for ARZM 01150 x B73). The same GEM accessions had the highest and lowest absolute densities among the GEM x Mo17 crosses (1.38 g/cc for Cuba 110 x Mo17 and 1.31 g/cc for ARZM 01150 x Mo17 and Piura 196 x Mo17).

Lambayeque 46, Piura 196, and ARZM 01150 crosses with the two inbreds had greater starch contents, and lower protein and fat contents. On the other hand, Cuba 110 had the lowest starch content and test weight, and the greatest fat content and absolute density among the GEM accessions. In general, the GEM accessions and their crosses had low starch contents, and high protein and fat contents.

Wet-milling Properties

The crosses wet milled better than did the GEM accessions (the GEM x B73 crosses had a mean starch yield of 58.4% and GEM x Mo17 crosses had a mean of 59.7% versus 54.5% for the GEM accessions) (Fig. 2A). The GEM x B73 crosses did not deviate greatly from the mean starch yields of the parents; but, the starch yields for the GEM x Mo17crosses were higher. The highest starch yield was for Lambayeque 46 x B73, and the greatest starch recovery was Lambayeque 46 x Mo17 (Fig. 2B). The lowest starch yield and recovery were observed for the Cuba 110 x Corn-Belt inbred and Guatamala 209 x Corn-Belt inbred crosses. Although the mean starch recovery of the GEM x B73 crosses was greater than for the GEM x Mo17 crosses, the GEM x Mo17 crosses gave greater starch recoveries than did the GEM x B73 crosses.

Protein contents of the recovered starches from most of the crosses were greater than typical industry acceptable limits (<0.3%). FS8A(S) x B73, FS8A(T) x B73, and Piura 196 x Mo17 had much better wet-milling properties (Fig. 2C). The mean protein content of the starches was greater for the crosses than for the GEM accessions (1.79% for the mean of the GEM x B73 crosses and 1.42% for the mean of the GEM x Mo17 crosses versus 1.10% for the mean of the GEM accessions). This is consistent with the higher protein contents and absolute densities of crosses.

Despite greater protein contents and absolute densities, gluten yields of the GEM x Corn-Belt inbred crosses were lower than those of the parent GEM accessions (13.7% for the mean of the GEM x B73 crosses and 12.9% for the mean of the GEM x Mo17 crosses versus 15.8% for the mean of the GEM accessions). Crossing the GEM accessions with Mo17 yielded less gluten than either parent. Despite the GEM x Mo17 crosses having greater gluten yields, they yielded less gluten than did the GEM x B73 crosses. The highest and lowest gluten yields were Cuba 110 x Mo17 and ARZM 01150 x B73, respectively.

The gluten protein content increased (means of 47.1% for the GEM x B73 crosses and 48.5% for the GEM x Mo17 crosses versus 41.1% for the GEM accessions); but, at the same time the residual protein content in starch also increased (1.79% for the mean of the GEM x B73 crosses and 1.42% for the mean of the GEM x Mo17 crosses versus 1.10% for the mean of the GEM accessions), which we attributed to higher levels of protein in the grain.

Mean fiber yields of the GEM x B73 crosses were greater than for either of the parents (a mean of 14.6% for GEM x B73 crosses versus means of 13.9 and 11.4% for GEM accessions and B73, respectively); but, yields of GEM x Mo17 crosses did not deviate greatly from the means of the parents (averaging 13.1% for GEM x Mo17 crosses versus 13.9 and 13.1% for the GEM accessions and Mo17, respectively) (Fig. 2D).

Despite B73 as a parent producing lower fiber yields than did Mo17, the GEM x B73 crosses resulted in greater fiber yields than did the GEM x Mo17 crosses. Poor fiber washing characteristics of the GEM x B73 crosses could be attributed to higher protein content of the grain. B73 crosses, having greater grain protein content, resulted in greater residual protein contents in the fiber perhaps acting as a binder between starch and fiber. We regularly observe corn with greater protein content and higher absolute density resulting in greater fiber yields and lower starch yields (Fox et al 1992).

The GEM x Corn-Belt inbred crosses yielded more germ than did the GEM accessions (a mean of 5.4% for the GEM x B73 crosses and a mean of 6.7% for the GEM x Mo17 crosses versus a mean of 5.1% for the GEM accessions). However, the two crosses had similar germ yields to their Corn-Belt inbred parents (5.1% for B73 and 6.8% for Mo17).

The GEM crosses yielded greater steepwater solids than did GEM accessions (means of 4.8% for the GEM x B73 crosses and 4.7% for the GEM x Mo17 crosses versus a mean of 4.5% for the GEM accessions). Despite B73 (4.0%) as a parent yielded lower steepwater solids than Mo17 (4.9%), the GEM x B73 crosses resulted in greater steepwater solids yields, which we attributed to the greater protein contents of the GEM x B73 crosses.

Filtrate solids yields for the GEM x Corn-Belt inbred crosses were lower than either of the parents (means of 2.9% for the GEM x B73 and 2.6% for the GEM x Mo17 crosses versus 3.8, 4.8, and 4.7% for the GEM accessions, B73, and Mo17, respectively).

Despite increased absolute density and protein content, starch yield and recovery increased, and gluten yield decreased for the crosses. Increased starch contents and decreased fat contents, however, contributed to the improved wet-milling performance of the crosses.

The GEM x B73 crosses exhibited additive effects for grain protein content and fiber yield, which are not desirable characteristics for wet-millability. The GEM x Mo17 crosses, on the other hand, exhibited additive effects for absolute density, grain starch content, starch yield, and starch recovery. Increased starch content was highly desired for improved wet-millability. Zehr et al (1995) have made similar observations. Although Mo17 as a parent possessed inferior wet-milling properties than B73, it produced crosses with superior properties.

Mid-parent Heterosis

Mid-parent heterosis was greater in the GEM x Mo17 crosses for absolute density, test weight, and 1000 kernel weight than in the GEM x B73 crosses (3.5, 5.1, and 23.0% for the GEM x Mo17 crosses versus 2.7, 0.46, and -8.3% for the GEM x B73 crosses, respectively) (Table IV). Mid-parent heterosis in the GEM x Mo17 crosses was greater for starch content (1.68% for the GEM x Mo17 crosses versus -0.45% for the GEM x B73 crosses), but lower for protein and fat contents (-2.7 and 2.4% for the GEM x Mo17 crosses versus 10.4 and 2.9% for the GEM x B73 crosses, respectively).

Mid-parent heteroses for starch yield and starch recovery were greater in the GEM x Mo17 crosses (6.9 and 5.2% for the GEM x Mo17 crosses and 0.65 and 1.26% for the GEM x B73 crosses, respectively). The GEM x Mo17 crosses had lower mid-parent heterosis for gluten and fiber yields than did the GEM x B73 crosses (-12.4 and -2.8% for the GEM x Mo17 crosses versus 0.37 and 13.8% for the GEM x B73, respectively). The crosses with Mo17 had better wet-milling characteristics than B73 crosses.

High-parent Heterosis

High-parent heterosis was greater in GEM x Mo17 crosses for absolute density, test weight, and 1000 kernel weight than in the GEM x B73 crosses (1.44, 1.92, and 7.99% for the GEM x Mo17 crosses versus 0.91, -0.56, and -16.01% for the GEM x B73 crosses, respectively) (Table V). High-parent heterosis in the GEM x Mo17 crosses was greater for starch content (1.13% for the GEM x Mo17 crosses versus -1.99% for the GEM x B73 crosses), but lower for protein and fat contents (-6.82 and -8.91 for the GEM x Mo17 crosses versus 6.78 and -5.02 for the GEM x B73 crosses, respectively).

High-parent heterosis for starch yield and starch recovery was greater in the GEM x Mo17 crosses (1.97 and 2.44% for the GEM x Mo17 crosses and -3.62 and -4.76% for the GEM x B73 crosses, respectively). The GEM x Mo17 crosses had lower high-parent heterosis for gluten and fiber yields than did the GEM x B73 crosses (-17.11 and -6.69% for the GEM x Mo17 crosses versus -11.3 and 4.79% for the GEM x B73 crosses, respectively).

CONCLUSIONS

The grain of the GEM accessions contain more protein and oil, are denser, and possess much poorer wet-milling properties than do commercial dent corn hybrids and Corn-Belt inbreds (Mo17 and B73). Crossing 10 selected GEM accessions with Mo17 and B73 increased protein content, decreased oil content, and increased absolute density and test weight. Starch yields increased in the crosses by almost 5 percentage points, but, are still at least 5 percentage points less than typical of commercial dent hybrids. The residual protein in the starches recovered from the crosses is also extraordinarily high (a mean of >1.5%) and unacceptable from an industry perspective; but, some crosses yielded starches with residual protein levels in the 0.4% range. Crossing the GEM accessions with Mo17 gave better starch yields and lower residual protein levels in the recovered starches than did crossing with B73. Mo17 expressed poor wet-milling properties as an inbred but produced superior hybrids than B73, which had better wet-milling properties as an inbred. Because Mo17 belongs to the non-Stiff Stalk heterotic pattern, breeders utilizing GEM breeding materials for improving wet-milling characteristics will likely want to look at lines developed from non-Stiff Stalk breeding crosses.

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TABLE I
Description of the 10 Selected GEM Accessions

Accession names	PI	Race	Kernel Color/Type	Area of Adaptation	Source
CHZM 05015	467165	Camelia	Orange Flint	Temperate	Chili, Valparaiso
Dominican Republic 150	484028	Mixed	Yellow Semident	Tropical	Dominican Republic
Cuba 110	489357	Argentino	Orange Flint	Tropical	Cuba
ARZM 01150	491741	Dent. Blanco Rugoso	White Dent	Temperate	Argentina, Buenos Aires
ARZM 13026	492746	Cristalino Colorado	Orange Flint	Temperate	Argentina, La Rioja
Guatemala 209	498583	Tuson	Yellow Flint	Tropical	Guatemala
Lambayeque 46	503732	Arizona	White Dent	Tropical	Peru, Lima
Piura 196	503844	Alazan	Red/White cap flour	Tropical	Peru, Lima
FS8A(S)	536619	Mixed	Yellow Semident	Temperate	US, Florida
FS8A(T)	536620	Mixed	Yellow Semident	Temperate	US, Florida

TABLE II
Compositional, Physical and Wet-Milling Properties of Selected GEM Accessions and Two Corn-Belt Inbreds[a]

	Compositional			Physical[b]			Wet-Milling								
	Str (%db)	Pro (%db)	Fat (%db)	TWt (lb/bu)	KnWt (g)	ADen (g/cc)	StrY (%db)	PiS (%db)	SRec (%)	Glu (%db)	PiG (%db)	Germ (%db)	Fib (%db)	SW (%db)	Fil (%db)
GEM Accessions															
CHZM 05 015	66.7	13.3	5.4	64.4	309.2	1.34	48.9	1.65	73.3	20.1	34.1	5.3	15.7	3.9	3.8
Dominican Republic150	68.4	12.6	4.4	66.3	276.1	1.35	56.0	1.26	81.9	12.9	43.2	4.1	16.6	4.8	3.0
Cuba 110	65.9	14.4	6.2	66.4	241.9	1.37	47.8	1.72	72.5	19.6	35.9	4.2	17.3	5 .0	3.4
ARZM 01 150	68.9	12.6	4.5	55.7	261.5	1.26	58.4	0.47	84.7	11.2	45.6	9.5	12.0	3.5	5.0
ARZM 130026	68.3	12.2	4.9	63.0	334.8	1.34	51.0	1.15	74.7	18.6	40.5	4.7	13.0	4.8	3.4
Guatemala 209	66.9	13.7	5.9	67.6	312.1	1.36	50.7	1.14	75.7	17.3	41.7	5.2	15.2	5.1	3.1
Lambayeque 46	66.9	13.7	5.9	67.6	312.1	1.36	50.7	0.88	75.7	17.3	41.7	5.2	15.2	5.1	3.1
Piura 196	66.6	12.0	3.9	56.9	291.5	1.17	61.9	0.57	92.9	12.9	51.0	3.4	10.6	4.3	4.6
FS8A(S)	68.3	12.6	5.8	64.7	301.3	1.33	55.0	0.78	80.5	15.9	36.8	4.9	13.8	4.8	3.5
FS8A(T))	68.6	12.5	5.6	64.2	360.1	1.32	56.9	1.16	83.0	14.9	36.9	4.2	13.5	4.2	3.6
Maximum	68.9	14.4	6.2	67.6	360.1	1.37	61.9	1.72	92.9	20.1	51.0	9.5	17.3	5.1	5.0
Minimum	65.9	12.0	3.9	55.7	241.9	1.17	47.8	0.57	72.5	11.2	34.1	3.4	10.6	3.5	3.0
Mean	67.7	12.9	5.2	62.6	303.9	1.30	54.5	1.10	80.6	15.8	41.1	5.1	13.9	4.5	3.8
Inbreds															
B73	69.7	11.9	4.3	63.6	360.3	1.29	62.4	0.53	89.5	11.4	52.4	5.1	11.4	4.0	4.8
Mo17	68.0	14.1	3.8	60.9	205.1	1.29	58.1	1.45	85.4	13.4	47.0	6.8	12.5	4.9	4.7

[a] Str = Starch content, Pro = Protein content, Fat = Crude free fat content, TWt = Test weight, KnWt = 1000 Kernel weight, ADen = Absolute density, StrY = Starch yield, PiS = Protein in starch , SRec = Starch recovery, Glu = Gluten yield, PiG = Protein in gluten , Fib = Fiber yield, SW = Steepwater solids yield, and Fil = Filtrate solids yield.

[b] All physical properties are reported on 15% moisture basis.

TABLE III
Compositional, Physical, and Wet-Milling Properties of GEM x B73 and GEM x Mo17 Crosses[a]

	Compositional			Physical[b]			Wet-Milling								
	Str (%db)	Pro (%db)	Fat (%db)	TWt (lb/bu)	KnWt (g)	ADen (g/cc)	StrY (%db)	PiS (%db)	SRec (%)	Glu (%db)	PiG (%db)	Germ (%db)	Fib (%db)	SW (%db)	Fil (%db)
GEM x B73 Crosses															
CHZM 05015 x B73	67.5	15.4	4.9	65.4	305.1	1.35	54.3	0.54	80.4	15.2	46.0	6.0	16.1	4.8	2.8
Dom. Rep. 150 x B73	69.5	13.0	4.6	66.7	289.7	1.35	58.4	2.40	84.1	12.8	38.7	4.7	16.2	5.1	2.3
Cuba 110 x B73	67.3	15.3	5.3	66.2	234.1	1.39	54.5	3.09	81.0	14.1	48.1	7.1	15.4	5.6	2.7
ARZM 01150 x B73	68.6	12.9	4.8	59.8	318.2	1.29	61.1	1.82	89.0	10.5	52.8	6.9	13.1	4.1	3.5
ARZM 130026 x B73	68.2	14.3	4.9	65.7	293.1	1.36	58.4	3.27	85.6	13.0	46.6	5.0	15.0	4.9	2.8
Guatamala 209 x B73	68.7	13.7	4.5	67.1	274.1	1.36	53.1	2.58	77.3	14.1	50.0	6.0	19.2	4.7	2.3
Lambayeque 46 x B73	68.3	13.4	5.1	61.8	309.8	1.31	62.6	0.62	91.6	13.9	51.3	4.5	12.0	4.6	3.4
Piura 196 x B73	69.9	12.7	3.6	56.9	371.8	1.31	62.5	0.66	89.4	13.9	50.9	3.5	12.3	5.0	3.8
FS8A(S) x B73	67.2	13.8	5.9	65.4	290.5	1.35	58.7	2.45	87.3	14.7	43.5	5.7	14.2	4.9	2.7
FS8A(T) x B73	67.9	12.8	5.6	64.5	339.9	1.33	60.9	0.49	89.7	15.0	42.7	5.0	12.7	4.6	2.6
Maximum	69.9	15.4	5.9	67.1	371.8	1.39	62.6	3.24	91.6	15.2	52.8	7.1	19.2	5.6	3.8
Minimum	67.2	12.7	3.6	56.9	234.1	1.29	53.1	0.49	77.3	10.5	38.7	3.5	12.0	4.1	2.3
Mean	68.3	13.7	4.9	64.0	302.6	1.34	58.4	1.79	85.5	13.7	47.1	5.4	14.6	4.8	2.9
LSD[c]	0.81	0.35	0.20	0.24	6.50	0.01	1.05	0.12	1.81	1.23	0.30	0.92	2.00	0.42	0.47
MO17 x GEM Crosses															
CHZM 05015 x Mo17	69.2	12.6	4.7	65.6	309.7	1.36	60.3	0.96	87.2	11.1	43.9	7.5	12.5	4.5	2.2
Dom. Rep. 150 x Mo17	70.4	12.6	4.2	67.2	259.7	1.37	58.4	0.97	82.9	12.0	47.8	6.0	15.0	4.9	2.4
Cuba 110 x Mo17	66.5	15.5	5.7	66.2	259.7	1.38	51.9	3.10	78.1	19.0	43.0	4.2	18.7	5.8	2.6
ARZM 01150 x Mo17	69.6	12.0	4.6	61.0	297.2	1.31	61.6	0.42	88.4	9.6	53.8	7.4	13.4	4.1	3.4
ARZM 130026 x Mo17	69.3	13.2	4.7	67.3	315.8	1.37	60.1	2.60	86.8	13.5	45.4	7.8	11.9	4.9	2.5
Guatamala 209 x Mo17	69.3	13.8	3.9	67.1	292.7	1.37	57.0	2.40	82.4	13.6	47.7	7.0	15.3	4.6	2.2
Lambayeque 46 x Mo17	68.9	12.9	4.7	63.0	363.3	1.32	63.4	0.41	92.0	11.6	54.2	6.8	11.0	4.6	2.8
Piura 196 x Mo17	70.2	12.1	3.3	63.0	373.1	1.31	64.2	0.45	91.5	12.4	55.5	5.8	10.2	4.6	3.4
FS8A(S) x Mo17	67.7	13.7	5.4	66.0	307.3	1.36	58.1	1.67	85.7	14.8	46.1	7.0	12.2	4.8	3.5
S8A(T) x Mo17	68.0	13.3	5.2	67.9	325.6	1.35	62.5	1.24	91.9	11.5	47.1	7.3	10.5	4.4	2.6

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[a] Str = Starch content, Pro = Protein content, Fat = Crude free fat Content, TWt = Test weight, KnWt = 1000 Kernel weight, ADen = Absolute density, StrY = Starch yield, PiS = Protein in starch, SRec = Starch recovery, Glu = Gluten yield, PiG = Protein in gluten, Fib = Fiber yield, SW = Steepwater solids yield, and Fil = Filtrate solids yield.

[b] All physical properties are reported on 15% moisture basis.

Table III. (Continued)

	Compositional			Physical[b]			Wet-Milling								
	Str (%db)	Pro (%db)	Fat (%db)	TWt (lb/bu)	KnWt (g)	ADen (g/cc)	StrY (%db)	PiS (%db)	SRec (%)	Glu (%db)	PiG (%db)	Germ (%db)	Fib (%db)	SW (%db)	Fil (%db)
Maximum	70.4	15.5	5.7	67.9	373.1	1.38	64.2	3.08	92.0	19.0	55.5	7.8	18.7	5.8	3.4
Minimum	66.5	12.0	3.3	61.0	259.7	1.31	51.9	0.41	78.1	9.6	43.0	4.2	10.2	4.1	2.2
Mean	68.9	13.2	4.6	65.4	310.4	1.35	59.7	1.42	86.7	12.9	48.5	6.7	13.1	4.7	2.6
LSD[c]	0.38	0.22	0.20	0.42	3.81	0.004	1.46	0.12	2.24	1.30	0.94	0.78	1.61	0.30	0.44

TABLE IV
Mid-Parent Heterosis in Compositional, Physical, and Wet-Milling Properties of GEM x B73 and GEM x Mo17 Crosses[a]

	Compositional			Physical[b]			Wet-Milling								
	Str (%db)	Pro (%db)	Fat (%db)	TWt (lb/bu)	KnWt (g)	ADen (g/cc)	StrY (%db)	PiS (%db)	SRec (%)	Glu (%db)	PiG (%db)	Germ (%db)	Fib (%db)	SW (%db)	Fil (%db)
GEM x Mo17 Crosses															
CHZM 05015 x B73	-1.0	22.2	1.0	2.2	-8.9	2.7	-2.4	-50.5	-1.2	-3.5	6.4	15.4	18.8	21.5	-34.9
Dom. Rep. 150 x B73	0.7	6.2	5.8	2.7	-9.0	2.3	-1.4	168.2	-1.9	5.4	-19.0	2.2	15.7	15.9	-41.0
Cuba 110 x B73	-0.7	16.4	1.0	1.9	22.3	4.5	-1.1	174.7	0.0	-9.0	9.0	52.7	7.3	24.4	-34.2
ARZM 01150 x B73	-1.0	5.3	9.1	0.3	2.4	1.2	1.2	264.0	2.2	-7.1	7.8	-5.5	12.0	9.3	-28.6
ARZM 130026 x B73	-1.2	19.2	6.5	3.8	-15.7	3.4	3.0	289.3	4.3	-13.3	0.3	2.0	23.0	11.4	-31.7
Guatamala 209 x B73	0.6	7.0	-11.8	2.3	-18.5	2.6	-6.1	209.0	-6.4	-1.7	6.3	16.5	44.4	3.3	-41.8
Lambayeque 46 x B73	0.0	4.7	0.0	-5.8	-7.9	-1.1	10.7	-12.1	10.9	-3.1	9.0	-12.6	-9.8	1.1	-13.9
Piura 196 x B73	2.6	6.3	-12.2	-5.6	14.1	6.5	0.6	20.0	-2.0	14.4	-1.6	-17.7	11.8	20.5	-19.2
FS8A(S) x B73	-2.6	12.7	16.8	2.0	-12.2	3.1	0.0	274.1	2.71	7.7	-2.5	14.0	12.7	11.4	-34.9
FS8A(T) x B73	-1.8	9.9	13.1	0.94	-5.6	1.9	2.1	-42.0	4.0	14.1	-4.4	7.5	2.0	12.2	-38.1
Mean	-0.45	10.4	2.9	0.46	-8.3	2.7	0.65	129.5	1.3	0.37	1.1	7.5	13.8	13.1	-31.8
GEM x Mo17 Crosses															
CHZM 05015 x Mo17	2.8	-8.0	2.2	4.7	20.4	3.4	12.7	-38.1	9.9	-33.7	8.3	24.0	-11.4	2.3	-48.2
Dom. Rep. 150 x Mo17	3.2	-5.6	2.4	5.7	7.9	3.8	2.4	-28.4	-0.9	-8.8	6.0	10.1	3.1	1.0	-37.7
Cuba 110 x Mo17	-0.7	8.8	14.0	4.0	16.2	3.8	-2.0	95.6	-1.1	15.2	3.7	-23.6	25.5	17.2	-35.8
ARZM 01150 x Mo17	1.7	-10.1	10.8	4.6	27.4	2.8	5.8	-56.3	3.9	-22.0	16.2	-9.2	9.4	-2.4	-29.9
ARZM 130026 x Mo17	1.7	0.4	8.1	8.6	17.0	4.2	10.2	100.0	8.4	-15.6	3.8	25.7	-6.7	1.0	-38.3
Guatamala 209 x Mo17	2.7	-0.7	-19.6	4.4	13.2	3.4	4.8	85.3	2.3	-11.4	7.6	16.7	10.5	-8.0	-43.6
Lambayeque 46 x Mo17	2.2	-7.2	-3.1	-2.0	40.5	-0.4	16.5	-64.8	14.2	-24.4	22.2	13.3	-20.6	-8.0	-28.2
Piura 196 x Mo17	4.3	-7.3	-14.3	7.0	50.3	6.5	7.0	-55.5	2.6	-5.7	13.3	13.7	-11.7	0.0	-26.9
FS8A(S) x Mo17	-0.7	2.6	12.5	5.1	21.4	3.8	2.7	49.8	3.3	1.0	10.0	19.7	-7.2	-1.0	-14.6
FS8A(T) x Mo17	-0.4	0.0	10.6	8.6	15.2	3.5	8.7	-5.0	9.1	-18.7	12.3	32.7	-19.2	-3.3	-37.4
Mean	1.7	-2.7	2.4	5.1	23.0	3.5	6.9	8.3	5.2	-12.4	10.3	13.3	-2.8	-0.12	-34.1

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[a] Str = Starch content, Pro = Protein content, Fat = Crude free fat Content, TWt = Test weight, KnWt = 1000 Kernel weight, ADen = Absolute density, StrY = Starch yield, PiS = Protein in starch, SRec = Starch recovery, Glu = Gluten yield, PiG = Protein in gluten, Fib = Fiber yield, SW = Steepwater solids yield, and Fil = Filtrate solids yield.

[b] All physical properties are reported on 15% moisture basis.

TABLE V
High-Parent Heterosis in Compositional, Physical, and Wet-Milling Properties of B73 x GEM and MO17 x GEM Crosses[a]

	Compositional			Physical[b]			Wet-Milling								
	Str (%db)	Pro (%db)	Fat (%db)	TWt (lb/bu)	KnWt (g)	ADen (g/cc)	StrY (%db)	PiS (%db)	SRec (%)	Glu (%db)	PiG (%db)	Germ (%db)	Fib (%db)	SW (%db)	Fil (%db)
GEM x B73 Crosses															
CHZM 05015 x B73	-3.1	15.9	-8.5	1.5	-15.3	0.75	-13.0	-67.3	-10.1	-24.6	-12.2	11.9	2.3	21.3	-42.0
Dom. Rep. 150 x B73	-0.2	3.0	4.3	0.5	-19.6	0.00	-6.3	86.5	-6.0	-0.9	-26.2	-7.3	-2.2	5.6	-51.6
Cuba 110 x B73	-3.5	6.5	-14.7	-0.2	35.0	1.46	14.0	79.7	-4.5	-28.3	-8.2	40.0	-10.8	13.0	-43.8
ARZM 01150 x B73	-1.5	2.1	7.1	-6.0	-11.7	0.00	-2.1	243.4	-0.5	-8.4	0.8	-27.4	9.6	1.4	-29.3
ARZM 130026 x B73	-2.1	17.0	0.0	3.2	-18.7	1.49	-6.3	184.4	-4.3	-29.9	-11.1	-1.1	15.6	1.1	-42.1
Guatamala 209 x B73	-1.5	-0.1	-24.2	-0.7	-23.9	0.00	-14.9	126.3	-13.6	-18.7	-4.6	15.2	26.6	-8.0	-52.1
Lambayeque 46 x B73	-2.0	6.1	1.2	-2.9	14.0	1.55	0.4	-29.6	2.4	-2.3	-2.1	-14.7	1.6	3.9	-29.2
Piura 196 x B73	0.3	5.9	-17.0	-2.9	3.2	1.55	0.3	15.8	-3.8	7.2	-2.9	-30.8	8.2	15.5	-21.1
FS8A(S) x B73	-3.6	9.2	2.1	1.4	-19.4	1.50	-5.9	214.1	-2.4	-7.6	-17.0	12.2	2.7	2.4	-43.8
FS8A(T) x B73	-2.6	2.2	-0.5	0.4	-5.7	0.76	-2.4	-57.8	0.3	0.6	-18.5	-0.9	-5.7	9.0	-44.4
Mean	-2.0	6.8	-5.0	-0.6	-6.2	0.91	-3.6	79.6	-4.3	-11.3	-10.2	-0.3	4.8	6.5	-39.9
GEM x Mo17 Crosses															
CHZM 05015 x Mo17	1.8	-10.6	-13.0	1.9	0.2	1.49	3.8	-41.8	18.8	-44.8	-6.6	10.3	-20.6	-8.2	-53.2
Dom. Rep. 150 x Mo17	3.0	-10.6	-4.6	1.3	-5.9	1.48	0.5	-33.1	1.2	-10.5	1.7	-11.8	-9.5	0.0	-48.9
Cuba 110 x Mo17	-2.2	7.6	-8.1	-0.2	7.4	0.73	-10.7	120.9	-8.7	-3.1	-8.5	-38.2	8.1	16.2	-44.7
ARZM 01150 x Mo17	1.0	-14.9	2.2	0.2	13.7	1.55	5.5	-71.0	3.6	-28.4	14.5	-21.8	7.2	-16.3	-32.0
ARZM 130026 x Mo17	1.5	-6.4	-4.1	6.9	-5.7	2.24	3.4	82.1	1.5	-27.4	-3.4	14.7	-8.4	0.0	-46.8
Guetamala 209 x Mo17	1.9	-2.1	-33.9	-0.8	-6.2	0.74	-1.9	64.1	-3.7	-21.6	1.5	2.9	0.7	-9.5	-53.2
Lambayeque 46 x Mo17	2.3	-8.5	-6.0	3.5	3.6	2.33	7.7	-71.7	5.2	-18.3	15.3	0.0	-12.0	-6.1	-40.4
Piura 196 x Mo17	3.2	-14.2	-15.4	3.5	28.0	1.55	3.8	-69.0	-1.6	7.5	8.8	-14.7	-18.4	-6.1	-26.4
FS8A(S) x Mo17	-0.9	-2.8	-6.9	-2.3	2.0	1.33	0.0	15.2	0.4	-7.0	-1.9	2.9	-11.5	-2.0	-46.8
FS8A(T) x Mo17	-0.3	-5.7	0.5	5.3	43.0	0.05	7.6	-14.5	7.6	-2.6	0.2	7.4	-2.5	-10.2	-44.7
Mean	1.1	-6.8	-8.9	1.9	8.0	1.35	2.0	-1.9	2.4	-15.6	2.2	-4.8	-6.7	-4.2	-43.7

[a] Str = Starch content, Pro = Protein content, Fat = Crude free fat Content, TWt = Test weight, KnWt = 1000 Kernel weight, ADen = Absolute density, StrY = Starch yield, PiS = Protein in starch, SRec = Starch recovery, Glu = Gluten yield, PiG = Protein in gluten, Fib = Fiber yield, SW = Steepwater solids yield, and Fil = Filtrate solids yield.

[b] All physical properties are reported on 15% moisture basis

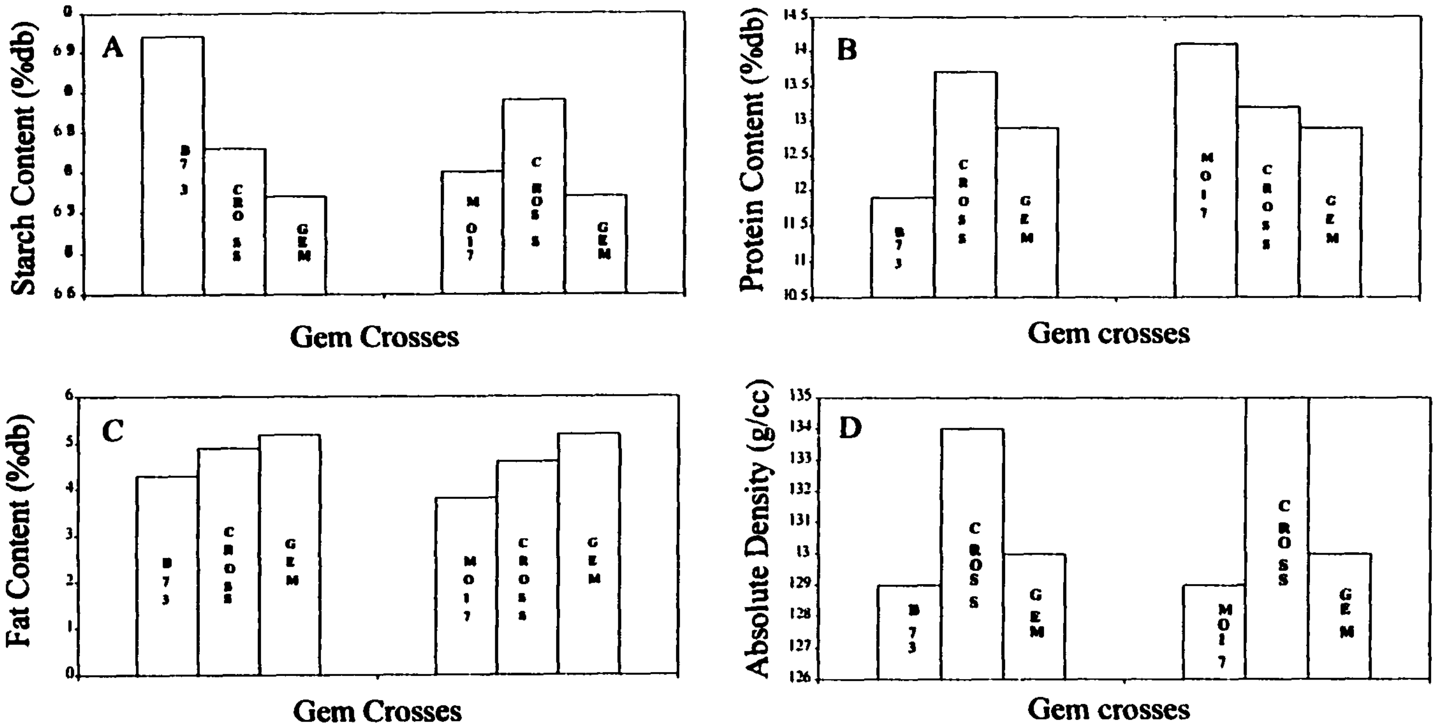

Fig. 1. Mean expressions of heterosis for compositional and physical properties of GEM crosses. Starch content (A), protein content (B), fat content (C), and absolute density (D).

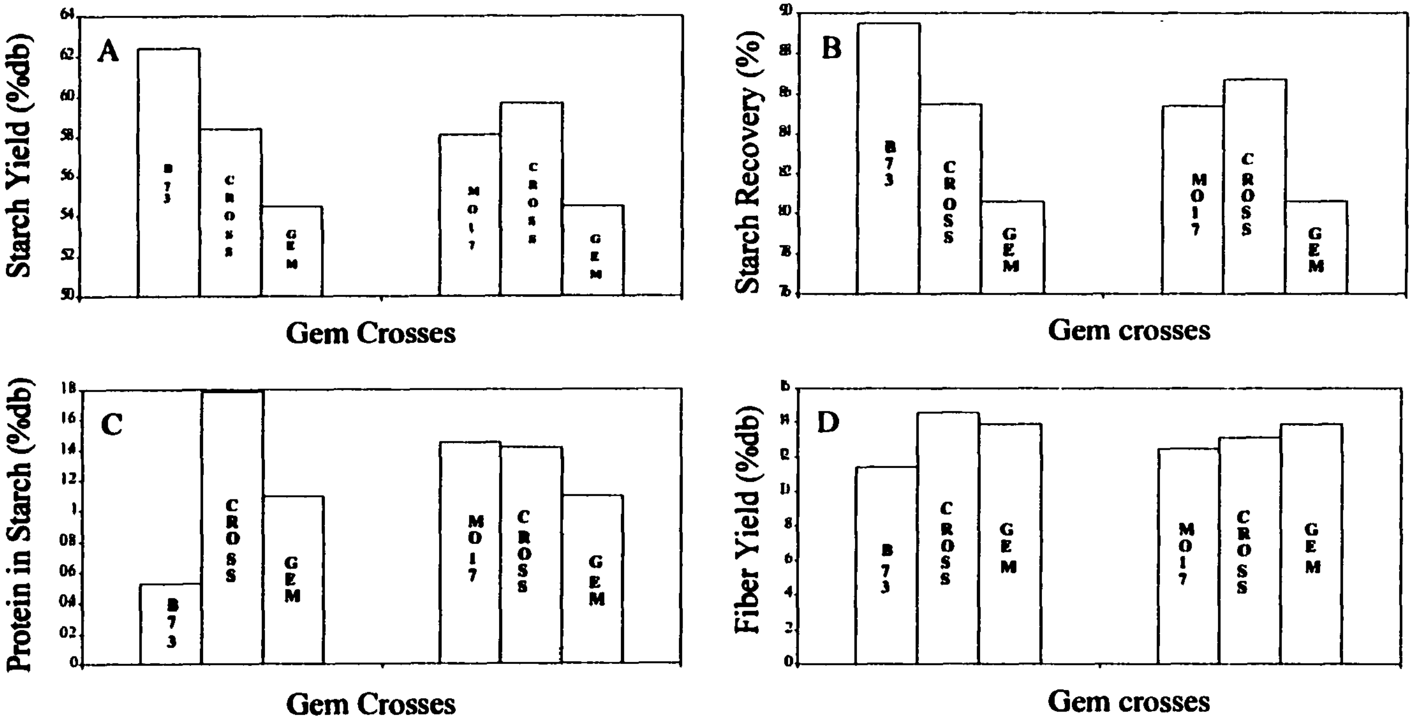

Fig. 2. Mean expressions of heterosis for wet milling properties of GEM crosses. Starch yield (A), starch recovery (B), protein yield (C), and fiber yield (D).

HETEROSIS IN PROPERTIES OF STARCHES RECOVERED FROM GEM x CORN-BELT INBRED CROSSES[1]

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ABSTRACT

Two common Corn-Belt inbreds were crossed with 10 GEM accessions that were selected for unusual starch thermal and pasting properties, as well as compositional, physical, and wet-milling properties. The starches were recovered and their functional properties were tested. The thermal properties of starches recovered from the GEM x B73 and GEM x Mo17 crosses ranged much less than starches from the GEM accessions. Crossing the GEM accessions with B73 and Mo17 inbreds gave similar starch thermal properties; but, mid-parent and high-parent heteroses were greater in the GEM x B73 crosses for all thermal properties, except for To and

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Tp of retrogradation. Values for all pasting properties increased over the values of either parent. One-day gel strengths were slightly less in the GEM x Corn-Belt inbred crosses than for the GEM accessions but greater than for either Corn-Belt inbred. Seven-day gel strengths were considerably reduced in the GEM x Corn-Belt inbred crosses, but greater than for either Corn-Belt inbred. Crossing B73 and Mo17 with GEM accessions resulted in unusually high pasting viscosities but reduced the unusually high gel strengths observed in GEM starches.

INTRODUCTION

Cornstarch is used in its native state and after chemical modification for a variety of food and industrial uses. Thermal, pasting (viscosity before, during and after cooking), and gelling properties are important functional properties to end-users. The starch industry is interested in developing new starches with unique functionalities not currently available in today's starch products and in developing natural starches, which possess functionality similar to those currently achieved by chemical modification.

Germplasm Enhancement of Maize Project (GEM) is a unique cooperation of the public and private sectors, which has initiated efforts to strengthen U.S. corn hybrids for increased yields, agronomic characteristics, and value-added traits (Pollak and Salhuana et al 1998). GEM is the successor to the Latin American Maize Project (LAMP) (Salhuana et al 1998) which was launched in 1987 by the U.S. Department of Agriculture, Agriculture Research Services (USDA/ARS) and 12 Latin American countries with funding from Pioneer Hi-Bred International (Johnston, IA). The principle goal of LAMP was to evaluate and maintain the irreplaceable corn germplasm bank of 12 Latin American countries and the USA.

LAMP evaluated 12,000 accessions grown at 70 locations in the United States and

Latin America. Screening was done on the basis of yield potential and agronomic characteristics. Two hundred sixty-eight of these accessions were selected as potential source of high yields, then 51 were chosen to initiate GEM.

Through recurrent selective breeding, exotic germplasm might be utilized to produce hybrids with unique traits and novelty starches. The value of using exotic germplasm for enhancing heterosis and genetic variability has long been recognized (Wellhausen et al 1965); but, little work has been undertaken relative to value-added traits. Heterosis is the superiority of the progeny over the parent and is widely used to improve yields and agronomic factors of corn. Zehr et al 1995 and Singh et al 1999a have assessed heterosis for improving compositional, physical, and wet-milling properties of corn.

Much work has already shown that thermal properties of maize starch varies considerably (Krueger et al 1987, Li et al 1994, Campbell et al 1995a, and Pollak and White 1997). However, except for starch mutant lines, most of the natural variation, while statistically significant, has not been practically significant to end-users. Attempts have been made to identify and enhance useful thermal properties of starch by selfing natural variants (Wang et al 1992, Wang et al 1993, Campbell et al 1994, 1995b). Pollak and White (1997) studied the thermal properties of a small population of crosses of exotic and Corn-Belt inbred lines; no consistent patterns were identified about the gelatinization and retrogradation properties in comparison with values for their parents.

In our previous work (Singh et al 2000a), we screened 49 GEM accessions, previously selected on the basis of yield and agronomic factors, for thermal, pasting, and gelling properties of starches recovered from these lines. The objective of the present study was to evaluate heterosis for thermal and pasting properties of starches from 10 selected GEM x

Corn-Belt dent inbred crosses and to gain insight about the underlying genetic control of these traits.

MATERIALS AND METHODS

Sample Preparation

The GEM accessions (Table I) were selected for diversity in compositional, physical, and wet-milling properties of the grains, and thermal, pasting, and gelling properties of the starches recovered from them. The corn selections were the same as those used by Singh et al (2000b) for evaluating heterosis in compositional, physical, and wet-milling properties of the grain. The 10 selected GEM accessions, the two Corn-Belt inbreds, and their crosses were grown during 1993 by, USDA-ARS, Department of Agronomy, Corn Insects and Crop Genetics Research Unit at the University Farm, Ames, IA.

Starch Isolation

The corn samples were dried and cleaned according to Singh et al (1999c) and wet milled using a 100-g laboratory-scale wet-milling procedure originally developed by Eckhoff et al (1996) and modified by Singh et al (1997).

Thermal Properties of Starch

The thermal properties of starches were determined by using procedures reported by Campbell et al (1994) and a differential scanning calorimeter (DSC) equipped with a thermal analyzer data station (DSC-7, Perkin-Elmer, Norwalk, CT). Starch samples (4 mg) and water (8 mg) was weighed in aluminum pans. The pans were sealed and allowed to equilibrate for 1 hr. The pans were heated from 30 °C to 120 °C at a rate of 10 °C/min in the DSC heating chamber. This was adequate temperature to completely gelatinize the starch. Values of onset temperature (To), peak temperature (Tp), and change in enthalpy (ΔH) for gelatinization were recorded. Peak Height Index (PHI) was calculated by dividing ΔH by the range [2*(Tp-To)]. After gelatinization, sample pans were stored at 4 °C for 7 days and then heated from 30 °C to 90 °C for reterogradation analysis. Values of To, Tp, ΔH for retrogradation were determined by DSC. %Retrogradation was calculated by dividing ΔH for retrogradation by the ΔH for gelatinization.

Pasting Properties of Starch

Pasting properties of the starches were determined by using a Rapid-Visco-Analyzer (RVA) (Model RVA 4, Newport Scientific, Warriewood, NSW, Australia), following the standard procedure (STD2) described in the Thermocline for WINDOWS: User's Manual (1995). An 8% (dwb) starch slurry with a final weight of 28 g was used. The STD2 profile involved equilibrating the slurry for 1 min. at 50 °C and increasing the temperature to 95 °C at the rate of 6 °C/min. The temperature was held at 95 °C for 5 min and then decreased to 50 °C at the rate of 6 °C/min. The temperature was held at 50 °C for 2 min. Peak Temperature (P_{temp}), Peak Viscosity (PV), Hot Paste Viscosity (HPV), Cold Paste Viscosity (CPV), Breakdown (BD), and Set Back (SB) values were recorded.

Gelling Properties of Starch

The starch pastes prepared in the RVA were poured into small aluminum canisters and stored at 4 °C to cause gelling. The textures (gel strengths) of the starch gels were determined after 1 and 7 days of storage at 4 °C using the procedure described by Wang et al (1992). Starch pastes were poured in a small aluminum dishes (27 mm, i.d. X 27 mm, h) and taped around the rim to increase the depth. After the storage period the gel sample was cut from the top to expose the fresh surface. Gel strengths were measured at five different locations of freshly exposed surface.

Statistics

An unpaired parametric, multiple comparison test (SAS 1984) was used to determine least significant differences (LSD) at levels $P < 0.05$, 0.01, and 0.001.

RESULTS AND DISCUSSION

Thermal Properties of Starch

The thermal properties of the starches from the 10 selected GEM accessions and their crosses with B73 and Mo17 are summarized in Tables II and III . Mid-parent and high-parent heterosis for the crosses are shown in Table IV and V, respectively. Onset gelatinization temperature (To) of the GEM x B73 crosses ranged from 68.6 to 70.6 °C, whereas the GEM X Mo17 crosses ranged from 69.0 to 69.9 °C. The mean gelatinization To value for both crosses were similar to their respective Corn-Belt inbred parents (70.6 °C for the GEM x B73 crosses versus 67.1 °C for the B73 inbred; 70.9 °C for the GEM X Mo17 crosses versus 69.4 °C for the Mo17 inbred). Lambayeque 46 x B73 and Dominican Republic 150 x B73 had the highest and lowest gelatinization To among the GEM x B73 crosses, whereas Piura 196 x Mo17 and Dominican Republic 150 x Mo17 had the highest and lowest gelatinization To among the GEM x Mo17 crosses.

The peak gelatinization temperatures (Tp) for the GEM x B73 crosses ranged from 73.9 to 73.1 °C for the GEM x B73 crosses and from 74.0 to 72.6 °C for the GEM X Mo17 crosses. The mean gelatinization To values of both crosses were similar (73.5 °C for the GEM x B73 crosses and 73.4 °C for the GEM X Mo17 crosses) (Fig. 1A). The peak gelatinization temperature for both crosses were greater than those of either Corn-Belt inbred but lower than those of the GEM accessions. Mean mid-parent heterosis of B73 crosses was larger for gelatinization To than that for Mo17 crosses (1.5 for B73 crosses versus 0 for Mo17 crosses) (Table IV), which indicates that starch granules of B73 crosses might be more ordered and compact. Gelatinization To might have also increased due to increased chain lengths of amylopectin present in the granules (Jane et al 1999).

Considerably higher enthalpies changes for gelatinization ($_{\Delta}$H) were observed in starches from the crosses (means of 14.6 J/g for the GEM x B73 crosses and 13.9 J/g for the GEM X Mo17 crosses versus a mean of 13.0 J/g for the GEM accessions). B73 (11.8 J/g), despite having lower $_{\Delta}$H for gelatinization than Mo17 (12.8 J/g), produced crosses with greater values of $_{\Delta}$H for gelatinization. The mean $_{\Delta}$H values for gelatinization of both crosses were greater than those of the respective parents indicating slightly greater difficulty in cooking (Fig. 1B). The highest and lowest $_{\Delta}$H values for gelatinization for the GEM x B73 crosses were Cuba 110 x B73 and CHZM 05015 x B73, respectively; whereas the highest and lowest $_{\Delta}$H for gelatinization for the GEM X Mo17 crosses were ARZM 01150 x Mo17 and Cuba 110 x Mo17, respectively. Larger values of mean mid-parent heterosis of B73 crosses for $_{\Delta}$H for gelatinization (15.4 for B73 crosses versus 6.9 for Mo17 crosses) (Table IV) suggest that the of amylose contents in B73 crosses decreased. McPherson and Jane (1999) have shown that increased amylose content decreases $_{\Delta}$H for gelatinization due to lack of native alignment of hydrogen bonds within starch molecule.

Peak height index (PHI), a measure of uniformity in gelatinization, ranged from 1.67 to 2.26 for the GEM x B73 crosses and 1.59 to 2.68 for the GEM X Mo17 crosses. The mean PHI values for each of the crosses were similar (1.96 and 2.03 for the GEM x B73 and the GEM X Mo17 crosses, respectively) (Fig. 1C). Both crosses had greater mean PHI values than did the values for either parent. Lambayeque 46 x B73 and Dominican Republic 150 x B73 had the highest and lowest PHI values among the GEM x B73 crosses, respectively; whereas Piura 196 x Mo17 and Dominican Republic 150 x Mo17 had the highest and lowest PHI among the GEM X Mo17 crosses, respectively. Increased PHI values for both crosses suggest decreased uniformity of starch granule size, which increases the gelatinization range and decreased proportions of amylose, which increase $_\Delta$H for gelatinization. Mid-parent heterosis of B73 crosses for PHI was larger than that of Mo17 crosses (18.1 for B73 crosses versus 8.7 for Mo17 crosses).

Onset retrogradation temperature (To), which is the temperature at which retrograded starch gels begin to absorb heat and loose crystalinity, of starches from GEM x Corn-Belt inbred crosses varied widely (36.4 to 44.7 °C for the GEM x B73 crosses versus 41.9 to 44.9 °C for the GEM X Mo17 crosses), but on average, the mean of the GEM x B73 crosses for retrogradation To was lower than the mean of the GEM X Mo17 crosses (41.6 °C for the GEM x B73 crosses versus 43.9 °C for the GEM X Mo17 crosses).

Change in enthalpies for retrogradation ($_\Delta$H), which are the amounts of heat required to destroy the crystalinity of retrograded starch gels, for the GEM x Corn-Belt inbred crosses also varied widely (6.32 to 8.08 J/g for the GEM x B73 crosses versus 6.20 to 7.66 J/g for the GEM X Mo17 crosses), but on average, the GEM X Mo17 crosses had lower $_\Delta$H values for retrogradation than did the GEM x B73 crosses (6.68 J/g for the GEM X Mo17 crosses versus 7.11 J/g for the GEM x B73 crosses). Greater variation of percent retrogradation (% Retro), which is the ratio of $_{\Delta}$H for gelatinization to $_{\Delta}$H for retrogradation, was observed in the GEM x B73 crosses than in the GEM X Mo17 crosses (45.0 to 56.3 % for the GEM x B73 crosses versus 45.1 to 53.7 % for the GEM X Mo17 crosses), but on average, % Retro values for both crosses were similar (48.6 % for the GEM x B73 crosses and 48.0% for the GEM X Mo17 crosses) (Fig. 1D). ARZM 01150 x B73 and Cuba 110 x B73 had the highest and lowest % Retro among the GEM x B73 crosses, respectively, whereas Piura 196 x Mo17 and ARZM 13026 x Mo17 had the highest and lowest % Retro among the GEM X Mo17 crosses, respectively. Increased values of %R for both crosses suggest increased proportions of amylose or amylopectin chain lengths, which contribute to re-association and hence increase retrogradation (Kasemsuwan et al 1995). Mid-parent heterosis of B73 crosses for %R was larger than that of Mo17 crosses (8.5 for B73 crosses versus 6.2 for Mo17 crosses).

Both crosses exhibited positive mid-parent and high-parent heterosis for gelatinization $_{\Delta}$H, and PHI, retrogradation $_{\Delta}$H, and % Retro. Negative mid-parent heterosis was observed for gelatinization To, gelatinization Tp, retrogradation To and retrogradation Tp. However, the expressions of heterosis for all four thermal properties were similar for both crosses. High PHI values and low values for gelatinization Tp, gelatinization $_{\Delta}$H, and % Retro values are desirable traits to end-users. Both crosses had lower gelatinization Tp, but greater gelatinization $_{\Delta}$H, indicating that the increase in PHI was largely due to increased gelatinization $_{\Delta}$H. Increased PHI is desirable, but not at the cost of increased gelatinization $_{\Delta}$H.

Among the GEM x B73 crosses, Dominican Republic 150 x B73 had the lowest and Piura

196 x B73 had the highest gelatinization To, gelatinization Tp, and PHI. Among the GEM X Mo17 crosses, Dominican Republic 150 x Mo17 had the lowest values for gelatinization Tp, gelatinization Tp, and retrogradation Tp, whereas Piura 196 x Mo17 had the highest values for gelatinization To, PHI, retrogradation $_\Delta H$, and % Retro. Cuba 110 x B73 crosses had the lowest % Retro and highest gelatinization $_\Delta H$. The same GEM accession when crossed with Mo17 had the lowest gelatinization $_\Delta H$, retrogradation $_\Delta H$, and PHI.

Pasting Properties of Starch

The pasting properties of pastes prepared from starches recovered from the 10 GEM accessions and their crosses with B73 and Mo17 are shown in Tables VI - IX. Relative performances of crosses and their parents are presented in Figures 5-10.

Pasting temperatures (P_{temp}) of the GEM x B73 crosses varied much more widely than did those of the GEM X Mo17 crosses (73.3 to 76.2 °C for the GEM x B73 crosses versus 72.4 to 74.0 °C for the GEM X Mo17 crosses) (Fig. 2A). Mean P_{temp} values for both crosses were lower than the values of their respective parents (74.1 °C for the GEM x B73 crosses and 73.1 °C for the GEM X Mo17 crosses versus 80.4, 77.7 and 75.6 °C for B73, Mo17, and the mean of the GEM accessions, respectively). CHZM 05015 x B73 and Lambayeque 46 x B73 had the highest and lowest P_{temp} values among the GEM x B73 crosses, respectively; whereas, Cuba 110 x Mo17 and Dominican Republic 150 x Mo17 had the highest and lowest P_{temp} values among the GEM X Mo17 crosses, respectively.

The starches recovered from the crosses had greater peak viscosities (PV) than did either parent (PV averaged 292 the GEM x B73 crosses and 200 RVU for the GEM X Mo17 crosses versus 101, 120, and 177 RV for B73, Mo17, and the mean of the GEM X Mo17 accessions, respectively) (Fig. 2B). FS8A(T) x B73 and Cuba 110 x B73 had the highest and lowest PV values among the GEM x B73 crosses, respectively. These same crosses had the highest and lowest hot paste viscosities (HPV). The highest and lowest PV for the GEM X Mo17 crosses were ARZM 13026 x Mo17 and Lambayeque 46 x Mo17, respectively; whereas, the highest and lowest HPV were FS8A(T) x Mo17 and FS8A(S) x Mo17, respectively. Contrary to the thermal properties of starches from the GEM accessions, which indicated properties typical of high amylose starch, the pasting properties of starches were similar to waxy starches. Higher PV values could result from increased proportions of amylopectin, which may relate to greater swelling and reduced free water (Zeng et al 1997).

The mean cold paste viscosity (CPV) of starches recovered from the GEM X Mo17 crosses were higher than for either parent (261 RVUs for the GEM X Mo17 crosses versus 214 and 249 RVU for Mo17 and the average of the GEM accessions, respectively). However, the mean CPV for the GEM x B73 crosses was similar to B73 but greater than the mean of the GEM accessions (277 RVU for the GEM x B73 crosses versus 277 and 249 RVU for B73 and the mean of the GEM accessions, respectively).

Breakdown (BD) values, which are the numerical differences of PV and HPV, of the GEM x Corn-Belt inbred crosses were considerably greater than those of their respective parents (150 RVU for the GEM x B73 crosses and 172 RVU for the GEM X Mo17 crosses versus 84, 88, and 99 RVU for B73, Mo17, and the mean of the GEM accessions, respectively) (Fig. 2C). On the other hand, setback (SB) values, which are the numerical differences of CPV and HPV, were considerably lower than those of their respective parents (134 RVU for the GEM x B73 crosses and 134 RVU for the GEM X Mo17 crosses versus 260, 182, and 171 RVU for B73, Mo17, and the mean of the GEM accessions, respectively)(Fig.2D). Piura 196 x B73 and Cuba 110 x B73 had the highest and lowest BD values among the GEM x B73 crosses, respectively, whereas Cuba 110 x Mo17 and CHZM 05015 x Mo17 had the highest and lowest BD values among the GEM X Mo17 crosses, respectively. Mean values of PV, HPV, and CPV of the GEM x Corn-Belt inbred crosses increased, but to different extents depending on the inbred. There was a positive expression of heterosis for BD, but a negative expression of heterosis for SB. Increased BD and decreased SB indicate that the crosses may have lower proportions of amylose or long chain amylopectin. Lower amylose content contributes to high swelling and thus has lower breakdown values (Jane 1999). The more swollen the starch granule, the more sensitive the starch paste is.

Similar expression of heterosis was observed for the pasting properties of both crosses. The GEM x B73 crosses had greater mid-parent and high-parent heteroses for PV and HPV, whereas for the remaining pasting properties, the GEM X Mo17 crosses had greater mid-parent and high-parent heteroses.

Gelling Properties of Starch

Average 1-day gel strengths for the GEM x Corn-Belt inbred crosses were greater than for the inbred lines but lower than for the GEM accessions (13.0 and 12.7 g for the GEM x B73 and GEM X Mo17 crosses, respectively, versus 10.0, 9.2, and 14.4 for B73, Mo17, and the mean of the GEM accessions, respectively) (Fig. 3A). Similar results were observed for starch gels stored for 7 days (27.5 g for the GEM x B73 crosses and 33.8 g for the GEM X Mo17 crosses versus 17.0, 23.3, and 45.9 g for B73, Mo17, and the mean of the GEM accessions, respectively) (Fig. 3B). Cuba 110 x B73 and Lambayeque 46 x B73 had the highest and lowest 1-day gel strengths among the GEM x B73 crosses, respectively, whereas

ARZM 13026 x Mo17 and CHZM 05015 x Mo17 had the highest and lowest 1-day gel strengths among the GEM X Mo17 crosses, respectively. Piura 196 x B73 and FS8A(S) x B73 had the highest and lowest 7-day gel strength among the GEM x B73 crosses, whereas Cuba 110 x Mo17 and Lambayeque 46 x Mo17 had the highest and lowest 7-day gel strengths among the GEM X Mo17 crosses, respectively. The expression of heterosis in the properties of starch gels stored at 4 °C for 1 and 7 days were similar for the GEM x B73 crosses and the GEM X Mo17 crosses, but mid-parent and high-parent heteroses were greater for the GEM x Mo17 crosses. Decreased proportion of amylose might have contributed to the decreased values of gel strengths for the crosses.

CONCLUSIONS

The ranges in thermal properties of starches recovered from the GEM x B73 and GEM X Mo17 crosses were much smaller than those of the GEM accessions. Crossing GEM accessions with B73 and Mo17 gave similar starch thermal properties; but, mid-parent and high-parent heteroses were greater in GEM x B73 crosses for all thermal properties except for retrogradation To and retrogradation Tp. Crossing B73 and Mo17 with GEM accessions results in unusually high pasting viscosities. One-day gel strengths were slightly less in the GEM x Corn-Belt inbred crosses than in for the GEM accessions but greater than either Corn-Belt inbred. Seven-day gel strengths were considerably reduced in the GEM x Corn-Belt inbred crosses, but still greater than for either Corn-Belt inbred. Crossing GEM accessions with two common Corn-Belt inbreds yielded starches with unusual pasting properties. Mo17 expressed poor starch thermal and pasting properties but produced hybrids with superior thermal and pasting than did B73.

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TABLE I
Description of the 10 Selected GEM Accessions

Accession names	PI	Race	Kernel Color/Type	Area of Adaptation	Source
CHZM 05015	467165	Camelia	Orange Flint	Temperate	Chili, Valparaiso
Dominican Republic 150	484028	Mixed	Yellow Semident	Tropical	Dominican Republic
Cuba 110	489357	Argentino	Orange Flint	Tropical	Cuba
ARZM 01150	491741	Dent. Blanco Rugoso	White Dent	Temperate	Argentina, Buenos Aires
ARZM 13026	492746	Cristalino Colorado	Orange Flint	Temperate	Argentina, La Rioja
Guatemala 209	498583	Tuson	Yellow Flint	Tropical	Guatemala
Lambayeque 46	503732	Arizona	White Dent	Tropical	Peru, Lima
Piura 196	503844	Alazan	Red/White cap flour	Tropical	Peru, Lima
FS8A(S)	536619	Mixed	Yellow Semident	Temperate	US, Florida
FS8A(T)	536620	Mixed	Yellow Semident	Temperate	US, Florida

TABLE II
Thermal Properties of Starches Recovered from Selected GEM Accessions[a]

Accesssion names	Gelatinization To (°C)	Gelatinization Tp (°C)	Gelatinization ΔH (J/g)	Gelatinization PHI (J/g/°C)	Retrogradation To (°C)	Retrogradation Tp (°C)	Retrogradation ΔH (J/g)	Retrogradation % Retro (%)
GEM accessions								
CHZM 05015	70.7	74.3	13.7	1.85	44.7	53.9	6.28	46.0
Dominican Republic 150	67.9	71.9	11.5	1.44	44.3	53.2	5.31	46.3
Cuba 110	70.4	74.1	13.5	1.85	44.5	53.8	6.63	49.1
ARZM 01150	71.8	74.0	12.9	1.97	46.8	55.8	6.06	47.0
ARZM 13026	69.3	73.4	13.4	1.66	44.6	53.3	6.53	48.9
Guatemala 209	69.6	73.6	12.7	1.60	44.0	52.8	6.01	47.4
Lambayeque 46	71.2	74.6	12.8	1.89	44.3	52.8	5.83	45.5
Piura 196	72.0	75.3	15.0	2.26	43.5	53.5	6.89	46.0
FS8A(S)	70.3	74.8	12.2	1.35	45.2	53.8	5.08	41.6
FS8A(T)	71.5	73.9	12.8	1.55	47.2	56.3	5.73	44.9
Maximum	72.0	75.3	15.0	2.26	47.2	56.3	6.89	49.1
Minimum	67.9	71.9	11.5	1.35	43.5	52.8	5.08	41.6
Mean	70.5	74.0	13.0	1.74	44.9	53.9	6.03	46.3
Inbreds								
B73	67.1	70.8	11.8	1.57	45.2	54.7	5.12	43.4
Mo17	69.4	72.7	12.8	1.98	44.2	52.8	5.71	44.2
LSD[b]	0.4	0.4	0.33	0.29	0.9	2.7	0.63	5.1

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[a] To = Onset temperature, Tp = Peak temperature, ΔH = Change in enthalpy, PHI = Peak height index , and % Retro = % Retrogradation.

[b] Least significant difference ($P < 0.05$).

TABLE III
Thermal Properties of Starches Recovered from GEM x B73 and GEM x Mo17 Crosses[a]

	Gelatinization				Retrogradation			
Accesssion names	To (°C)	Tp (°C)	ΔH (J/g)	PHI (J/g/°C)	To (°C)	Tp (°C)	ΔH (J/g)	% Retro (%)
GEM x B73 crosses								
CHZM 05015 x B73	69.8	73.5	13.5	1.80	43.8	52.6	6.32	46.7
Dominican Republic 150 X B73	68.6	73.1	15.2	1.67	44.2	53.2	6.95	45.9
Cuba 110 X B73	69.8	73.3	15.3	2.13	40.9	51.7	6.82	44.4
ARZM 01150 X B73	70.1	73.7	14.4	2.01	38.5	51.1	8.08	56.3
ARZM 13026 X B73	69.8	73.2	14.3	2.13	36.4	49.5	7.70	54.0
Guatemala 209 X B73	69.6	73.8	14.0	1.72	40.7	50.5	7.20	51.3
Lambayeque 46 X B73	70.6	73.9	15.0	2.26	42.5	52.4	6.99	47.2
Piura 196 X B73	70.4	73.7	14.7	2.18	42.7	51.7	6.78	46.1
FS8A(S) X B73	69.6	73.5	15.0	1.88	42.0	50.0	7.20	45.0
FS8A(T) X B73	69.7	73.7	14.3	1.80	44.7	53.4	7.07	49.5
Maximum	70.6	73.9	15.3	2.26	44.7	53.4	8.08	56.3
Minimum	68.6	73.1	13.5	1.67	36.4	49.5	6.32	45.0
Mean	69.8	73.5	14.6	1.96	41.6	51.6	7.11	48.6
LSD[b]	0.3	0.3	0.29	0.17	1.2	2.0	0.50	4.0
GEM X Mo17 crosses								
CHZM 05015 x Mo17	69.6	73.3	13.9	1.88	44.9	53.1	6.53	47.3
Dominican Republic 150 x Mo17	70.0	72.6	14.1	1.93	44.6	53.9	6.36	45.2
Cuba 110 x Mo17	69.1	73.2	13.1	1.59	44.5	53.4	6.20	47.1
ARZM 01150 x Mo17	70.5	73.8	14.7	2.18	44.0	53.1	6.91	47.1
ARZM 13026 x Mo17	69.3	72.7	13.9	2.01	44.5	48.2	6.24	45.1
Guatemala 209 x Mo17	69.3	73.0	13.5	1.80	41.9	51.8	6.61	48.9
Lambayeque 46 x Mo17	70.8	74.0	14.4	2.26	44.3	53.1	6.82	47.3
Piura 196 x Mo17	70.9	73.6	14.3	2.68	43.7	53.1	7.66	53.7
FS8A(S) x Mo17	69.8	73.3	13.6	1.97	44.3	53.2	6.66	48.9
FS8A(T) x Mo17	70.5	73.9	13.8	2.05	42.7	53.4	6.82	49.4

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[a] To = Onset temperature, Tp = Peak temperature, ΔH = Change in enthalpy, PHI = Peak height index, and % Retro = % Retrogradation.

[b] Least significant difference ($P < 0.05$).

Table III. (Continued)

Accesssion names	Gelatinization				Retrogradation			
	To (°C)	Tp (°C)	ΔH (J/g)	PHI (J/g/°C)	To (°C)	Tp (°C)	ΔH (J/g)	% Retro (%)
Maximum	70.9	74.0	14.7	2.68	44.9	52.9	7.66	56.3
Minimum	69.0	72.6	13.1	1.59	41.9	48.2	6.20	45.0
Mean	69.9	73.4	13.9	2.03	43.9	52.5	6.68	48.6
LSD[b]	0.4	0.4	0.33	0.21	0.9	2.7	0.63	5.1

TABLE IV
Mid-Parent Heterosis of Thermal Properties for Starches Recovered from GEM x B73and GEM x Mo17 Crosses[a]

	Gelatinization				Retrogradation			
Accesssion names	To (°C)	Tp (°C)	ΔH (J/g)	PHI (J/g/°C)	To (°C)	Tp (°C)	ΔH (J/g)	% Retro (%)
GEM x B73 crosses								
CHZM 05015 x B73	1.3	1.3	6.0	5.4	-2.4	-3.1	10.7	4.5
Dominican Republic 150 x B73	1.6	2.4	30.1	11.5	-1.1	-1.4	33.4	2.4
Cuba 110 x B73	1.5	1.3	20.9	24.2	-8.8	-4.7	16.3	-3.8
ARZM 01150 x B73	1.0	1.8	16.2	13.6	-16.3	-7.5	44.4	24.4
ARZM 13026 x B73	2.4	1.5	13.4	31.9	-18.9	-8.2	13.4	16.9
Guatemala 209 x B73	1.8	2.1	14.4	7.6	-8.7	-6.0	29.3	13.0
Lambayeque 46 x B73	2.1	1.7	1.7	29.5	-5.0	-2.5	28.2	6.2
Piura 196 x B73	1.2	0.1	9.7	13.7	-3.7	-4.4	12.7	3.1
FS8A(S) x B73	1.2	1.0	25.2	28.6	-7.1	-7.8	41.4	5.8
FS8A(T) x B73	0.6	1.8	16.2	15.0	-3.3	-3.9	30.5	12.1
Mean	1.5	1.5	15.4	18.1	-7.5	-5.0	26.0	8.5
GEM x Mo17 crosses								
CHZM 05015 x Mo17	-0.5	-0.3	4.6	-1.2	1.0	-0.4	0.9	4.8
Dominican Republic 150 x Mo17	0.5	0.5	16.0	13.3	0.7	1.8	15.7	0.0
Cuba 110 x Mo17	-1.2	-0.3	-0.3	-16.3	-0.2	-0.1	-0.3	0.9
ARZM 01150 x Mo17	-0.2	0.6	14.2	11.4	-3.2	-2.2	17.4	3.2
ARZM 13026 x Mo17	-0.1	-0.4	6.0	11.7	0.2	-9.2	2.4	-3.0
Guatemala 209 x Mo17	-0.0	-0.0	6.1	1.7	-5.1	-1.8	3.1	6.8
Lambayeque 46 x Mo17	0.7	0.5	12.3	16.6	0.0	0.5	18.1	5.4
Piura 196 x Mo17	0.3	-0.5	2.7	26.7	-0.3	-0.2	21.5	19.0
FS8A(S) x Mo17	-0.1	-0.6	8.8	17.9	-1.0	-0.2	23.3	13.8
FS8A(T) x Mo17	0.0	0.8	8.1	15.5	-6.6	-4.0	19.1	10.9
Mean	-0.1	0.0	6.9	8.7	-1.5	-1.6	13.1	6.2

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[a] Mid-parent heterosis = 100*(cross - average of the GEM accessions and the Corn-Belt inbred)/average of the GEM accessions and the Corn-Belt inbred; To = Onset temperature, Tp = Peak temperature, ΔH = Change in enthalpy, PHI = Peak height index, and % Retro = % Retrogradation.

TABLE V
High-Parent Heterosis of Thermal Properties for Starches Recovered from GEM x B73 and GEM x Mo17 Crosses[a]

Accesssion names	Gelatinization				Retrogradation			
	To (°C)	Tp (°C)	ΔH (J/g)	PHI (J/g/°C)	To (°C)	Tp (°C)	ΔH (J/g)	% Retro (%)
GEM x B73 crosses								
CHZM 05015 x B73	-1.2	-1.1	-1.2	-2.0	-3.0	-3.8	0.4	1.5
Dominican Republic 150 x B73	1.0	1.7	28.2	6.1	-2.2	-2.8	30.9	-0.8
Cuba 110 x B73	-0.9	-1.0	13.3	15.6	-9.5	-5.5	2.9	-9.3
ARZM 01150 x B73	-2.4	-0.4	11.3	2.8	-17.7	-8.4	33.0	19.6
ARZM 13026 x B73	0.1	-0.0	6.8	29.4	-19.5	-9.5	17.8	10.3
Guatemala 209 x B73	0.0	0.0	10.5	7.3	-9.9	-7.7	19.6	8.2
Lambayeque 46 x B73	-0.8	-0.9	16.9	19.5	-5.9	-4.2	20.2	3.7
Piura 196 x B73	-2.2	-2.1	-2.0	-3.2	-5.6	-5.5	-1.8	0.2
FS8A(S) x B73	-1.1	-1.7	23.2	19.0	-7.1	-8.6	40.9	3.7
FS8A(T) x B73	-2.5	-0.3	11.9	13.5	-5.4	-5.2	23.4	10.3
Mean	-1.0	-0.6	11.9	10.8	-8.6	-6.2	18.7	4.7
GEM x Mo17 crosses								
CHZM 05015 x Mo17	-1.4	-1.4	1.3	-4.2	0.4	-1.4	4.2	2.8
Dominican Republic 150 x Mo17	-0.6	-0.1	9.9	-2.0	0.6	0.1	1.8	-2.3
Cuba 110 x Mo17	-1.9	-1.2	-2.8	-18.9	-0.2	-0.8	-6.8	-4.1
ARZM 01150 x Mo17	-1.9	-0.3	13.8	11.5	-5.8	-4.8	13.9	0.0
ARZM 13026 x Mo17	-0.2	-0.9	3.8	2.7	-0.3	-9.5	-4.2	-7.7
Guatemala 209 x Mo17	-0.5	-0.8	5.6	-7.8	-5.3	-1.8	10.1	3.2
Lambayeque 46 x Mo17	-0.5	-0.8	12.3	14.2	-0.2	0.5	16.7	3.9
Piura 196 x Mo17	-1.4	-2.2	-4.8	18.4	-1.1	-0.8	10.9	16.7
FS8A(S) x Mo17	-0.7	-2.1	6.2	-0.5	-2.1	-1.2	16.7	10.5
FS8A(T) x Mo17	-1.5	0.0	8.0	3.2	-9.6	-7.0	18.8	10.1
Mean	-1.0	-0.9	5.7	2.0	-2.3	-2.6	8.9	3.5

[a] High-parent heterosis = 100*(cross - high parent)/high parent; To = Onset temperature, Tp = Peak temperature, ΔH = Change in enthalpy, PHI = Peak height index, and % Retro = % Retrogradation.

TABLE VI
Pasting and Gelling Properties of Starches Recovered from Selected GEM Accessions[a]

Accession names	Pasting Properties						Gel Strength	
	PV (RVU)	HPV (RVU)	CPV (RVU)	P_{temp} (°C)	BD (RVU)	SB (RVU)	1 day (g)	7 days (g)
GEM accessions								
CHZM 05015	135	30	243	78	105	213	12.0	32.4
Dominican Republic 150	187	83	233	73	104	150	15.3	42.5
Cuba 110	118	26	246	78	92	220	9.5	29.8
ARZM 01150 (ARZM 01 150)	249	136	242	74	113	106	11.9	45.4
ARZM 13026 (ARZM 13 026)	139	38	248	77	102	210	12.2	36.0
Guatemala 209 (NRC 5595)	176	71	248	76	104	176	14.9	61.0
Lambayeque 46	194	85	257	76	109	172	15.7	50.8
Piura	163	75	246	76	87	170	14.2	40.4
FS8A(S)	201	109	263	75	92	154	18.8	54.7
FS8A(T)	210	125	264	74	85	139	19.2	66.2
Maximum	249	136	264	78	113	220	19.2	66.2
Minimum	118	26	233	73	85	106	9.5	29.8
Mean	177	78	249	76	99	171	14.4	45.9
Corn-Belt inbreds								
B73	101	17	277	80	84	260	10.0	17.0
Mo17	120	32	214	78	88	182	9.2	23.3
LSDd[b]	16	19	17	1	14	28	1.0	2.2

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[a] PV = Peak viscosity, HPV = Hot paste viscosity, CPV = Cold paste viscosity, P_{temp} = Pasting temperature, BD = Breakdown (PV-HPV,), SB = Setback (CPV-HPV,); and 1 day and 7 days = Gel strength after 1 and 7 days storage at 4°C, respectively.

[b] Least significant difference ($P < 0.05$).

TABLE VII
Pasting and Gelling Properties of Starches Recovered from GEM x B73 and GEM x Mo17 Crosses[a]

	Pasting Properties						Gel Strength	
	PV (RVU)	HPV (RVU)	CPV (RVU)	P_{temp} (oC)	BD (RVU)	SB (RVU)	1 day (g)	7 days (g)
GEM x B73 crosses								
CHZM 05015 x B73	194	95	180	76	99	85	11.2	24.7
Dominican Republic 150 x B73	292	135	278	73	158	142	13.4	30.9
Cuba 110 x B73	278	114	235	74	164	122	10.1	26.5
ARZM 01150 x B73	289	145	259	74	144	114	12.9	26.0
ARZM 13026 x B73	285	136	268	75	150	132	12.5	27.3
Guatemala 209 x B73	295	144	281	74	152	138	14.1	29.0
Lambayeque 46 x B73	294	143	281	73	160	137	15.9	31.0
Piura 196 x B73	281	160	310	74	120	150	15.7	23.0
FS8A(S) x B73	297	139	281	74	158	142	11.0	31.4
FS8A(T) x B73	317	175	305	73	142	130	12.8	25.3
Maximum	320	175	310	76	164	310	15.9	31.4
Minimum	278	114	235	73	120	114	10.1	23.0
Mean	292	143	277	74	150	134	13.0	27.5
LSD[b]	13	24	6	1	20	24	1.0	1.4
GEM x Mo17 crosses								
CHZM 05015 x Mo17	304	112	253	73	192	141	13.4	30.6
Dominican Republic 150 x Mo17	315	134	279	72	181	145	12.4	32.8
Cuba 110 x Mo17	284	140	293	74	145	154	12.3	29.7
ARZM 01150 x Mo17	306	123	253	73	183	130	12.7	33.5
ARZM 13026 x Mo17	319	135	267	73	184	133	11.7	30.3
Guatemala 209 x Mo17	300	122	245	74	179	123	12.6	34.7
Lambayeque x Mo17	283	120	257	74	163	137	13.0	39.7
Piura 196 x Mo17	284	136	277	73	148	141	13.3	33.8
FS8A(S) x Mo17	291	111	233	73	181	122	12.8	35.3
FS8A(T) x Mo17	313	145	255	73	168	95	13.3	37.3

[a] PV = Peak viscosity, HPV = Hot paste viscosity, CPV = Cold paste viscosity, P_{temp} = Pasting temperature, BD = Breakdown (PV-HPV,), SB = Setback (CPV-HPV,), and 1 day and 7 day = Gel strength after 1 and 7 days of storage at 4°C, respectively.

[b] Least significant difference ($P < 0.05$).

Table VII. (Continued)

	Pasting Properties						Gel Strength	
	PV (RVU)	HPV (RVU)	CPV (RVU)	P_{temp} (°C)	BD (RVU)	SB (RVU)	1 day (g)	7 days (g)
Maximum	320	145	293	74	192	154	13.4	39.7
Minimum	283	111	263	72	145	95	11.7	29.7
Mean	200	128	261	73	172	132	12.7	33.8
LSD[b]	16	19	17	1	14	28	1.0	2.2

TABLE VIII

Mid-Parent Heterosis of Pasting and Gelling Properties for Starches Recovered from GEM x B73 and GEM x Mo17 Crosses[a]

	Pasting Properties						Gel Strength	
Cross	PV (RVU)	HPV (RVU)	CPV (RVU)	P_{temp} (°C)	BD (RVU)	SB (RVU)	1 day (g)	7 days (g)
GEM x B73 crosses								
CHZM 05015 x B73	147.2	512.0	3.8	-3.8	56.9	-46.3	1.9	0.0
Dominican Republic 150 x B73	103.1	171.6	8.8	-4.1	66.9	-30.6	5.9	3.8
Cuba 110 x B73	154.3	438.3	-10.0	-6.8	86.4	-49.3	3.6	13.3
ARZM 01150 x B73	65.6	90.0	0.0	-4.7	46.7	-37.6	17.9	-16.7
ARZM 13026 x B73	138.0	400.3	2.0	-4.3	61.3	-4.4	12.6	3.0
Guatemala 209 x B73	113.7	226.6	7.3	-5.2	60.8	-36.8	13.1	-25.7
Lambayeque 46 x B73	99.5	182.2	5.1	-6.2	66.1	-36.5	23.8	-8.5
Piura 196 x B73	113.3	248.5	18.8	-5.3	40.6	-30.3	29.5	-19.9
FS8A(S) x B73	97.1	120.7	3.9	-4.5	80.2	-31.4	-23.7	-12.4
FS8A(T) x B73	103.8	146.9	12.7	-5.0	67.6	-35.0	-12.2	-39.2
Mean	113.6	253.7	5.2	-5.0	63.4	-33.8	7.3	-10.2
GEM x M17 crosses								
CHZM 05015 x Mo17	138.4	258.4	10.6	-6.9	99.4	-28.6	26.5	9.8
Dominican Republic 150 x Mo17	105.2	133.0	24.8	-3.7	88.4	-12.9	1.2	-0.3
Cuba 110 x Mo17	139.2	381.2	27.5	-5.2	61.1	-23.5	31.6	11.9
ARZM 01150 x Mo17	66.1	46.0	10.9	-4.3	82.9	-9.8	20.5	-2.5
ARZM 13026 x Mo17	146.3	284.5	15.7	-5.7	95.0	-32.4	9.3	2.2
Guatemala 209 x Mo17	103.2	134.4	6.0	-4.0	86.4	-31.3	4.4	-17.7
Lambayeque 46 x Mo17	80.4	104.6	9.0	-4.1	66.0	-22.8	4.5	7.2
Piura 196 x Mo17	100.9	152.3	20.5	-4.5	69.2	-19.9	13.5	6.1
FS8A(S) x Mo17	81.9	56.8	-2.5	-4.3	101.6	-27.5	-8.6	-10.2
FS8A(T) x Mo17	89.9	84.2	6.7	-3.6	94.9	-40.8	-6.2	-16.6
Mean	105.1	163.5	12.9	-4.6	84.5	-24.9	9.7	-0.9

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[a] Mid-parent heterosis = 100*(cross - average of the GEM accession and the Corn-Belt inbred)/average of the GEM accession and the Corn-Belt inbred; PV = Peak viscosity, HPV = Hot paste viscosity, CPV = Cold paste viscosity, P_{temp} = Pasting temperature, BD = Breakdown (PV-HPV), SB = Setback (CPV-HPV), and 1 day and 7 days = Gel strength measured after 1 and 7 days storage at 4°C, respectively.

TABLE IX

High-Parent Heterosis of Pasting and Gelling Properties for Starches Recovered from GEM x B73 and GEM x Mo17 Crosses[a]

Cross	Pasting Properties						Gel Strength	
	PV (RVU)	HPV (RVU)	CPV (RVU)	P_{temp} (°C)	BD (RVU)	SB (RVU)	1 day (g)	7 days (g)
GEM x B73 crosses								
CHZM 05015 x B73	115.9	375.0	-2.6	-5.2	41.4	-51.2	-6.6	-23.8
Dominican Republic 150 x B73	56.2	63.0	0.3	-8.7	50.8	-45.3	-12.5	-27.3
Cuba 110 x B73	135.8	343.9	-15.1	-8.0	78.2	-53.2	1.0	-11.0
ARZM 01150 x B73	16.2	6.6	-6.4	-8.4	27.9	-56.1	8.5	-42.7
ARZM 13026 x B73	105.0	260.4	-3.4	-6.3	47.4	-49.3	2.4	-24.2
Guatemala 209 x B73	68.0	101.2	1.6	-8.0	45.2	-47.0	175.1	-52.5
Lambayeque 46 x B73	51.6	68.7	1.4	-8.8	47.3	-47.3	1.4	-39.0
Piura 196 x B73	72.7	112.6	12.1	-8.2	38.1	-42.3	10.3	-43.1
FS8A(S) x B73	48.0	27.2	1.3	-7.8	72.7	-45.4	-41.6	-42.6
FS8A(T) x B73	50.7	39.8	10.1	-8.7	66.6	-50.1	-33.2	-61.8
Mean	64.8	123.9	-3.3	-7.8	46.8	-50.4	-7.6	-36.8
GEM x Mo17 crosses								
CHZM 05015 x Mo17	125.3	245.4	4.1	-7.1	83.1	-33.8	11.8	-5.6
Dominican Republic 150	68.3	62.0	17.7	-6.8	73.3	-20.4	-19.0	-22.8
Cuba 110 x Mo17	137.0	330.5	19.3	-5.6	57.1	-30.2	29.6	-0.2
ARZM 01150 x Mo17	66.1	46.0	10.9	-4.3	82.9	-9.8	20.5	-2.5
ARZM 13026 x Mo17	129.2	257.7	7.8	-6.2	81.6	-36.9	-4.2	-15.8
Guatemala 209 x Mo17	71.0	70.5	-1.2	-5.3	71.4	-32.4	-15.7	-43.2
Lambayeque 46 x Mo17	46.0	41.3	-0.0	-5.3	49.9	-24.8	-17.1	-21.8
Piura 196 x Mo17	74.6	80.4	12.8	-5.8	68.8	-22.4	-6.6	-16.4
FS8A(S) x Mo17	45.3	1.7	-11.6	-6.0	97.0	-32.9	-32.0	-36.0
FS8A(T) x Mo17	49.0	15.9	-3.4	-5.9	92.2	-47.7	-30.6	-43.7
Mean	76.9	109.5	5.2	-6.0	73.7	-31.0	-7.7	-23.1

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[a] High-parent heterosis = 100*(cross - high parent)/high parent; PV = Peak viscosity, HPV = Hot paste viscosity, CPV = Cold paste viscosity, P_{temp} = Pasting temperature, BD = Breakdown (PV-HPV,), SB = Setback (CPV-HPV,), and 1 day and 7 days = Gel strength measured after 1 and 7 days storage at 4°C, respectively.

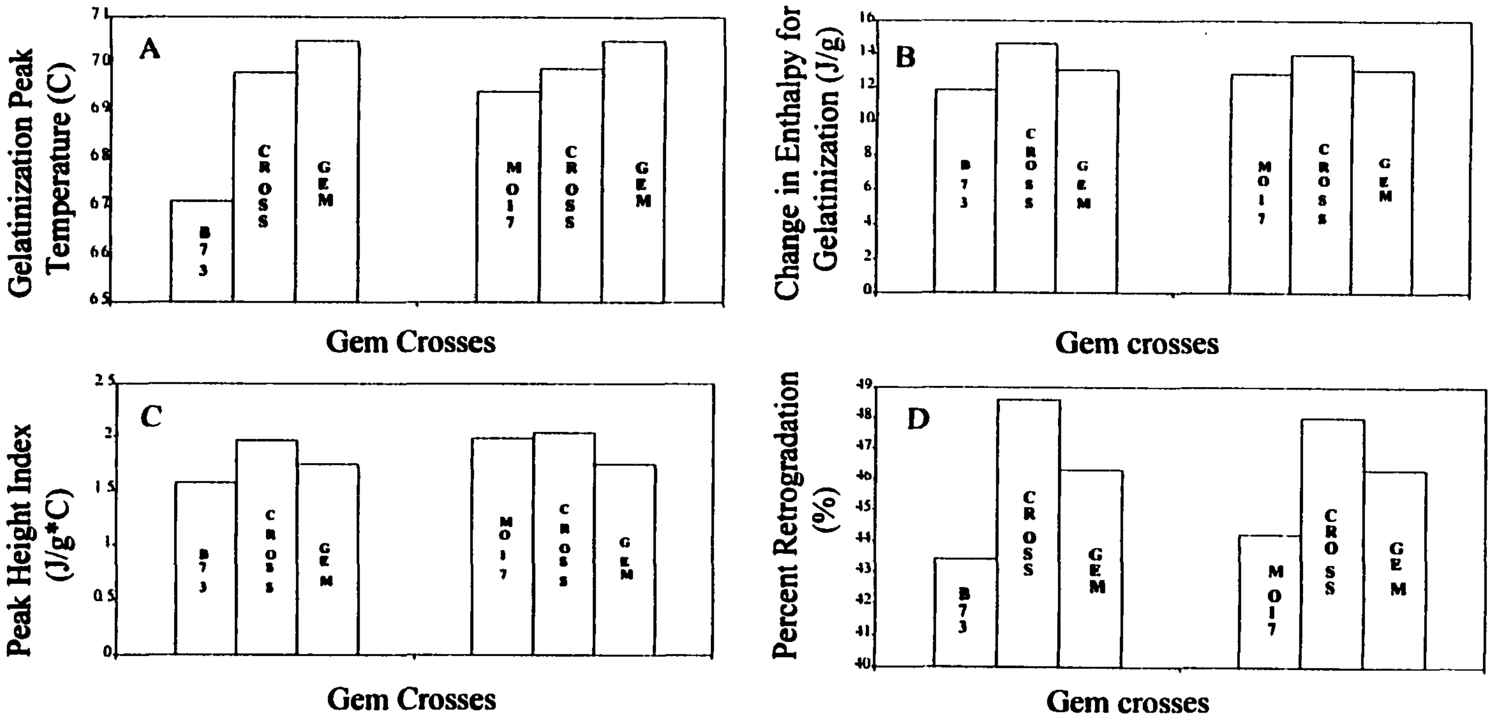

Fig. 1. Mean expressions of heterosis for thermal properties of GEM crosses. Gelatinization onset temperature (A), change in enthalpy of gelatinization (B), peak height index (C), and percent retrogradation (D).

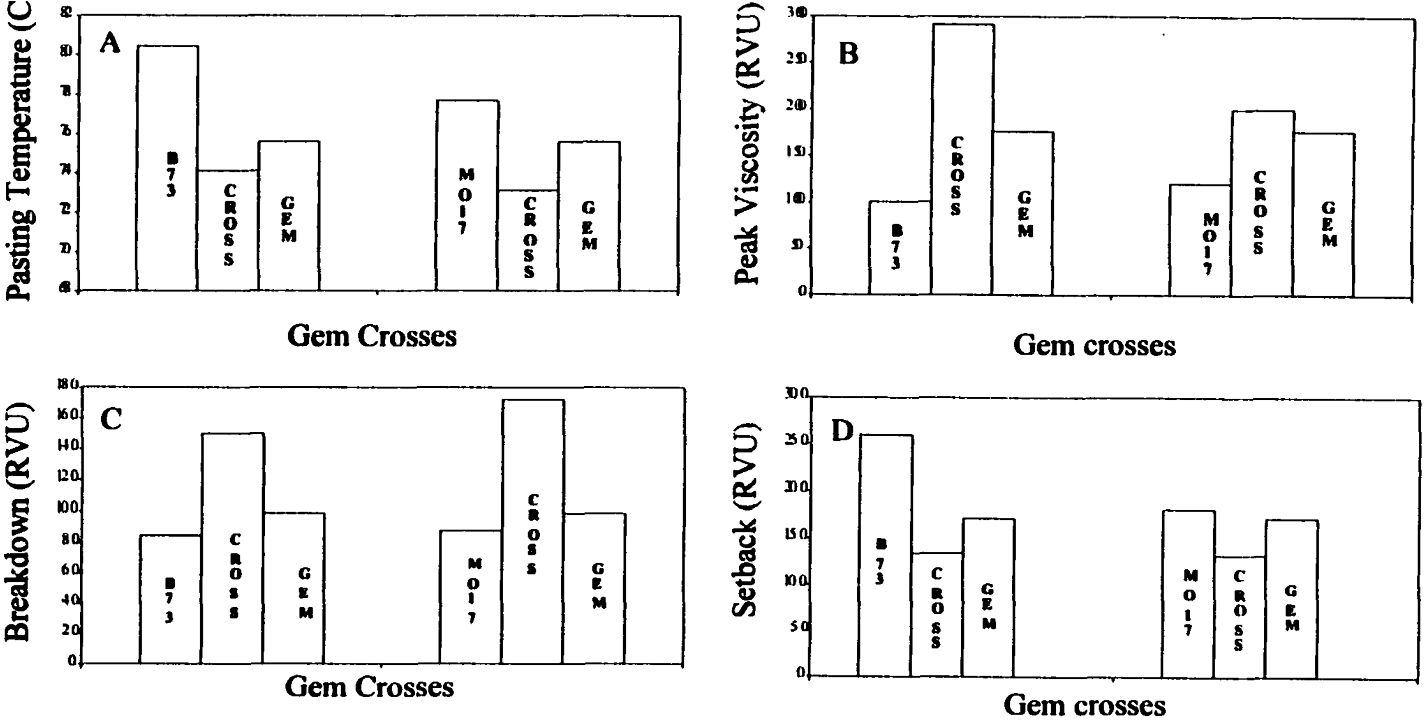

Fig. 2. Mean expressions of heterosis for pasting properties of GEM crosses. Pasting temperature (**A**), peak viscosity (**B**), breakdown (**C**), and setback (**D**).

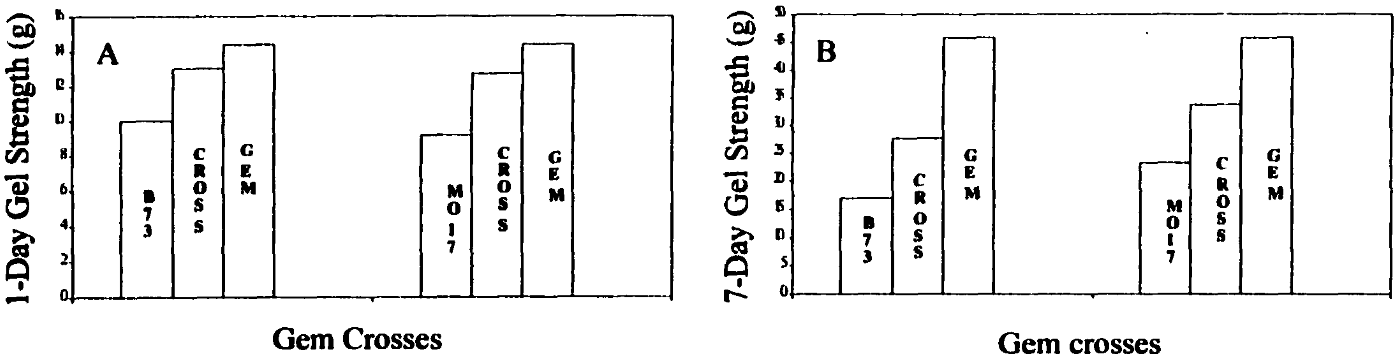

Fig. 3. Mean expressions of heterosis for gelling properties of GEM crosses. 1-day gel strength (**A**), 7-day gel strength (**B**).

GENERAL CONCLUSION

The modified 100-g and 1-Kg procedures produced similar starch and gluten yields (62-67% and 9-12%, respectively) and also values similar to those achieved by industry. Our pilot-plant (10 Kg) procedure produced slightly lower starch and greater gluten yields (59-64%), which we attributed to difficulty in achieving complete starch separation from fiber and gluten using pilot-plant equipment. Protein contents of the starch and gluten in all three procedures were similar (0.2-0.4% and 36-47% respectively). The protein contents of the starch produced by all three procedures were within acceptable limits (<0.5%). Waxy corn produced lower starch yields (52-60%) with lower residual protein contents in starch (0.18-0.22%), but greater gluten yields (10-17%).

Rankings of four hybrids (3 commercial normal dent hybrids and 1 waxy hybrid) based on starch yields and starch recovery were the same for all three procedures. The harder the grain the poorer the yields of starch in all procedures. The larger the scale of wet milling the less precise the method is. The least significant differences ($P < 0.05$) for starch yield were 0.8% for the modified 100-g procedure, 1.2% for the 1-Kg procedure, and 2.0% for the pilot-plant procedure.

The significantly greater speed of the modified 100-g procedure (4-5 samples per day per person) and the excellent reproducibility make it useful for screening large numbers of corn samples. Although our pilot-plant procedure is slower (2-3 days using two technicians per sample) and less reproducible than other methods and produced lower starch and higher gluten and fiber yields, it is useful in some instances to determine differences in millability of hybrids, but more importantly to obtain large amounts of representative materials from genetically modified hybrids for applications development. Laboratory and pilot-plant wet-milling procedures now seem adequate for most research objectives.

Forty-nine GEM accessions selected for high yield and other desirable agronomic factors were screened for compositional, physical, and wet-milling properties. The accessions did not wet mill nearly as good as did commercial dent hybrids, which was attributed to several compositional and physical factors. The accessions had considerably lower starch contents (65.9-69.1%) and greater protein (12.0-14.4%) and fat (3.9-6.2%) contents than does commercial dent hybrids and Corn-Belt inbreds. However, higher levels of protein and fat, and high absolute density indicate that the accessions are energy dense and good for livestock feed. Higher protein contents the accessions indicate good dry-milling characteristics.

The mean starch yield was 54.3% for the accessions compared with 64.8% for the commercial hybrids. The residual protein content of the recovered starches ranged 0.45-2.03% for the accessions compared to <0.3% for the commercial hybrids. Poor starch-gluten separation in the accessions was attributed to the high protein content of the accessions and resulted in high residual protein in the recovered starch and low protein content in the gluten. High fiber yields indicated poor fiber-washing characteristics of the accessions. Our data indicate that the best accessions for wet milling are those which have high starch and low protein contents, and low absolute density and test weights.

The thermal, pasting, and gelling properties of the starches recovered from the accessions varied widely. In general, the values for onset temperature of gelatinization, peak temperatures of gelatinization, and peak height indices of starches recovered from the accessions were greater, but, heats of gelatinization were less for the starches recovered from the accessions than for normal commercial starches. On average, retrogradation properties were similar for starches recovered from the accessions and the commercial hybrids, although there were some specific accessions with starches possessing modestly different retrogradation properties. Peak viscosities, final viscosities, and viscosity beakdowns were greater for starches recovered from the accessions than for the starches recovered from the commercial hybrids. Pasting temperatures were about the same for all of the starches. Both 1-day and 7-day gel strengths were considerably greater for the starches recovered from the accessions, some were accessions had starches with 2-3 times the gel strength of starches from commercial hybrids. Although differences in properties of starches recovered from the accessions were statistically significant, only differences in gel strengths were of practical significance.

Thermal properties were relatively poorly correlated with pasting and gelling properties. Differential scanning calorimetry, Rapid visco-analyzer and evaluating the gels strengths with a Voland Texture Analyzer give extensive information of the functional properties of starches and these rapid techniques should be useful to breeding programs.

Few consistent patterns of heterosis in heritability of compositional, physical, and wet-milling traits were observed when crossing GEM accessions with two common Corn-Belt dent inbreds (B73 and Mo17). Crossing GEM accessions with the Corn-Belt inbreds increased the protein contents, decreased oil content, and increased absolute density and test weight compared to the GEM accessions. On wet milling the yields of starches from the crosses were almost 5 percentage points better than the GEM parent but are still a least 5 percentage points less than typical commercial dent hybrids. The residual protein levels also increased in starches recovered from the crosses over values observed in either parent. The mean residual protein levels in starches recovered from the crosses was <1.5%; but, some crosses yielded starches with protein levels in the 0.4% range. Crossing the GEM accessions with Mo17 gave better starch yields and lower residual protein levels in the recovered starches than did crossing with B73.

Few consistent patterns of heterosis in thermal, pasting, and gelling properties were observed when crossing GEM accessions with two common Corn-Belt dent inbreds. The ranges in values for the thermal properties of starches recovered from the crosses were much smaller than for the GEM accessions. There was no advantage in using one inbred over the other; but, there was more heterosis in GEM x B73 crosses than for GEM x Mo17 crosses for most thermal properties. All pasting values increased over the values for either parent, which was not expected and might be exploited to increase variation in pasting properties. One-day gel strengths were slightly less in the crosses than in the GEM accessions, but greater than either Corn-Belt inbred. Seven-day gel strengths were considerably reduced in the starches recovered from the crosses from those of the GEM accessions, which was the unique property observed in starches recovered from GEM accessions. Crossing GEM with Corn-Belt inbreds yields starches with unusual pasting properties.

The present work has developed and compared wet milling procedures for 100 g to 10 Kg of corn. We have also examined GEM accessions for unusual processing properties and functional properties of starch. We have shown that GEM accessions have unusual gelling properties. Upon crossing with Corn-Belt inbreds those unique gelling properties were lost but unusual pasting properties developed. Genes for these traits may be useful in corn breeding programs to develop hybrids with unique value-added traits.