Heterosis in Compositional, Physical, and Wet-Milling Properties of Adapted × Exotic Corn Crosses[1]

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ABSTRACT

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Compositional, physical, and wet-milling properties of 10 corn accessions selected from the Germplasm Enhancement of Maize (GEM) project, two Corn Belt Dent inbreds (B73 and Mo17), and their crosses were compared to determine heterosis among these traits and to gain insight about their genetic control. Crossing the GEM accessions with each inbred increased protein and reduced starch contents. Mean absolute densities and test weights of the crosses were greater than for either parent. Little heterosis was observed in 1,000-kernel weight, and the crosses had similar values to the 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 content in the recovered starch, whereas values for protein in starch for the GEM × Mo17 crosses were greater than for the GEM accessions and not unlike that of Mo17. High-parent heterosis was greater in the GEM × Mo17 crosses for absolute density, test weight, 1,000-kernel weight, and starch content, but lower for protein and fat contents. GEM × 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 compared with B73, which had better wet-milling properties as an inbred.

Heterosis is the superiority of hybrid progeny over inbred parents for the trait of interest, which is usually grain yield. Both midparent heterosis and high-parent heterosis are used by maize breeders. Midparent 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. Although heterosis is normally applied to plant vigor, it can also be applied to other seed traits such as compositional, physical, and wet-milling properties, which are the subjects of the present article.

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 midparent values and attributed lower germ and fiber yields, and 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 that 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) that was launched in 1987 by the United States Department of Agriculture Agriculture Research Services (USDA-ARS) and 11 Latin American countries with funding from Pioneer Hi-Bred International (Johnston, IA). The principal goal of LAMP was to evaluate and maintain the irreplaceable corn germplasm bank material of Latin America and the United States.

LAMP evaluated over 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. Of these accessions, 270 were selected as potential sources of high yields, with 51 chosen to initiate GEM. The objective of the present study was to evaluate heterosis of compositional, physical, and wet-milling properties in selected GEM × 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) were selected for crossing with two widely used public Corn Belt Dent inbreds (Mo17 and B73) on the basis of extreme values for compositional, physical, and wet-milling properties of the grain and for thermal, pasting, and gelling properties of the starches recovered from them. The selected accessions and Corn Belt inbreds were grown and crossed in a nursery near Ponce, 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 Approved Method 44-15A (AACC 2000). Starch, protein, and crude free fat contents (dry basis) were estimated in triplicate by using an Infratec grain analyzer (model 1225), a near-infrared transmittance (NIR-T) analyzer (Tecator, Hoganas, Sweden). The grain analyzer calibration process is described in Rippke et al (1996). A running database of corn spectra on U.S. and international samples has been updated yearly, beginning in 1986. All known types of flint and dent corn are included in this database. Calibrations were validated annually and updated as needed based on validation results. Wet-chemistry references were provided by Woodson Tenant Labs (Des Moines, IA) for protein, oil, and starch and by the Iowa State University Grain Quality Laboratory for moisture and density. The reference methods were Kjeldahl (protein), ether extraction (oil), glucose hydrolysis (starch), air oven (moisture), and nitrogen pycnometer (density). Specific methods are described in Rippke et al (1996).

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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. The 1,000-kernel weight was determined by using an electronic counter (Syntron, Homer City, PA) to count kernels. Values were determined in triplicate and adjusted to 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 (CRA) 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 Institute, Cary NC) 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 2.

Compositional Properties

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

The crosses contained considerably more protein than did the GEM accessions (13.7% for the GEM × B73 crosses and 13.2% for the GEM × Mo17 crosses vs. 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 × Mo17 and ARZM 01150 × Mo17, respectively.

The mean oil content of the crosses did not deviate greatly from the mean of the parents (4.9% for GEM × B73 crosses and 4.6% for GEM × Mo17 crosses vs. 5.2, 4.3, and 3.8% for GEM accessions, B73, and Mo17, respectively) (Fig. 1C), suggesting that proportions of germ did not differ. FS8A(S) × B73 had the highest (5.9%) and Piura 196 × Mo17 (3.8%) the lowest oil contents among the crosses.

Physical Properties

The 1,000-kernel weights of the crosses also varied widely (234–371 g for GEM × B73 crosses and 260–373 g for GEM × Mo17 crosses), but the mean 1,000-kernel weights of the crosses were similar to the mean of the GEM accessions (303 g for GEM × Mo17 and 310 g for GEM × B73 crosses vs. 304 g for GEM accessions).

Test weights ranged from 56.9 to 67.1 lb/bu for the GEM × B73 crosses and from 61.0 to 67.9 lb/bu for the GEM × Mo17 crosses but, on average, test weights of the crosses were greater than for either parent (64.0 lb/bu for the GEM × Mo17 crosses and 65.4 lb/bu for the GEM × B73 crosses vs. 62.6, 63.6, and 60.9 lb/bu for the GEM accessions, B73, and Mo17, respectively).

Absolute densities of the crosses ranged from 1.29 to 1.39 g/cm^3 for the GEM × B73 crosses and from 1.31 to 1.38 g/cm^3 for the GEM × Mo17 crosses but, on average, absolute densities of the crosses were higher than those of the parents (1.34 g/cm^3 for the GEM × B73 and 1.35 g/cm^3 for the GEM × Mo17 crosses vs. 1.30, 1.29, and 1.29 g/cm^3 for the GEM accessions, B73, and Mo17, respectively) (Fig. 1C). Accessions Cuba 110 and ARZM 01150 gave the highest and lowest absolute densities among the GEM × B73 crosses, respectively (1.39 g/cm^3 for Cuba 110 × B73 and 1.29 g/cm^3 for ARZM 01150 × B73). The same GEM accessions had the highest and lowest absolute densities among the GEM × Mo17 crosses, respectively (1.38 g/cm^3 for Cuba 110 × Mo17 and 1.31 g/cm^3 for ARZM 01150 × Mo17 and Piura 196 × 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 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 × B73 crosses had a mean starch yield of 58.4% and GEM × Mo17 crosses had a mean of 59.7% vs. 54.5% for the GEM accessions) (Fig. 2A). The GEM × B73 crosses did not deviate greatly from the mean starch yields of the parents, but the starch yields for the GEM × Mo17 crosses were higher. The cross producing the highest starch yield was Lambayeque 46 × B73, and the greatest starch recovery was Lambayeque 46 × Mo17 (Fig. 2B). The cross producing the lowest starch yield and recovery were observed for the Cuba 110 × Corn Belt inbred and Guatemala 209 × Corn Belt inbred crosses, respectively. Although the mean starch recovery of the GEM × B73 crosses was greater than for the GEM × Mo17 crosses, the GEM × Mo17 crosses gave greater starch recoveries than did the GEM × B73 crosses.

TABLE I
Selected Accessions of Germplasm Enhancement of Maize Project

Accession	PI	Race	Kernel Color/Type	Area of Adaptation	Source
CHZM 05015	467165	Camelia	Orange Flint	Temperate	Chile, 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

Protein contents of recovered starches from most crosses were greater than typical industry acceptable limits (<0.3%) (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 × B73 crosses and 1.42% for the mean of the GEM × Mo17 crosses vs. 1.10% for the mean of the GEM accessions). This is consistent with the higher protein contents and absolute densities of the crosses.

Despite greater protein contents and absolute densities, gluten yields of the GEM × Corn Belt inbred crosses were lower than those of the parent GEM accessions (mean values of 13.7% for GEM × B73 crosses and 12.9% for GEM × Mo17 crosses vs. 15.8%

TABLE II
Compositional, Physical, and Wet-Milling Properties of Selected Germplasm Enhancement of Maize (GEM) Project Accessions and Two Corn Belt Inbreds[a,b]

	Compositional			Physical			Wet-Milling[c]								
Accession	**Str**	**Pro**	**Fat**	**TWt**	**KWt**	**ADen**	**StrY**	**PiS**	**SRec**	**Glu**	**PiG**	**Germ**	**Fib**	**SW**	**Fil**
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 Rep. 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	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 (lb/bu), KWt = thousand-kernel weight (g), ADen = absolute density (g/cm^3), StrY = starch yield, PiS = protein in starch, SRec = starch recovery, Glu = gluten yield, PiG = protein in gluten, Germ = germ yield, Fib = fiber yield, SW = steepwater solids yield, and Fil = filtrate solids yield.

[b] Compositional and wet-milling properties are reported as %db. All physical properties are reported on 15% moisture basis.

[c] Indicated as %db, except SRec as %.

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

	Compositional			Physical			Wet Milling[c]								
Cross	**Str**	**Pro**	**Fat**	**TWt**	**KWt**	**ADen**	**StrY**	**PiS**	**SRec**	**Glu**	**PiG**	**Germ**	**Fib**	**SW**	**Fil**
GEM × B73 Crosses															
CHZM 05015 × 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 × 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 × 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 × 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 × 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
Guatemala 209 × 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 × 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 × 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) × 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) × 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[d]	0.8	0.4	0.2	0.2	6.5	0.01	1.1	0.12	1.8	1.2	0.3	0.9	2.0	0.4	0.5
GEM × Mo17 Crosses															
CHZM 05015 × 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 × 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 × 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 × 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 × 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
Guatemala 209 × 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 × 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 × 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) × 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) × 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
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[d]	0.4	0.2	0.2	0.4	3.8	0.01	1.5	0.12	2.2	1.3	0.9	0.8	1.61	0.3	0.4

[a] GEM = Germplasm Enhancement of Maize Project, Str = starch content, Pro = protein content, Fat = crude free fat content, TWt = test weight (lb/bu), KWt = thousand-kernel weight (g), ADen = absolute density (g/cm^3), StrY = starch yield, PiS = protein in starch, SRec = starch recovery, Glu = gluten yield, PiG = protein in gluten, Germ = germ yield, Fib = fiber yield, SW = steepwater solids yield, and Fil = filtrate solids yield.

[b] Compositional and wet-milling properties are reported as %db. All physical properties are reported on 15% moisture basis.

[c] Indicated as %db, except SRec as %.

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

for GEM accessions). Crossing the GEM accessions with Mo17 yielded less gluten than did either parent. The GEM × Mo17 crosses yielded less gluten than did the GEM × B73 crosses. The crosses producing the highest and lowest gluten yields were Cuba 110 × Mo17 and ARZM 01150 × B73, respectively.

The gluten protein content increased (mean values of 47.1% for GEM × B73 crosses and 48.5% for GEM × Mo17 crosses vs. 41.1% for GEM accessions) but, at the same time, the residual protein content in starch also increased (1.79% for the mean of the GEM × B73 crosses and 1.42% for GEM × Mo17 crosses vs. 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 × B73 crosses were greater than for either parent (mean of 14.6% for GEM × B73 crosses vs. 13.9 and 11.4% for the GEM accessions and B73, respectively), but yields of GEM × Mo17 crosses did not deviate greatly from the means of the parents (13.1% for GEM × Mo17 crosses vs. 13.9 and 13.1% for the GEM accessions and Mo17, respectively) (Fig. 2D).

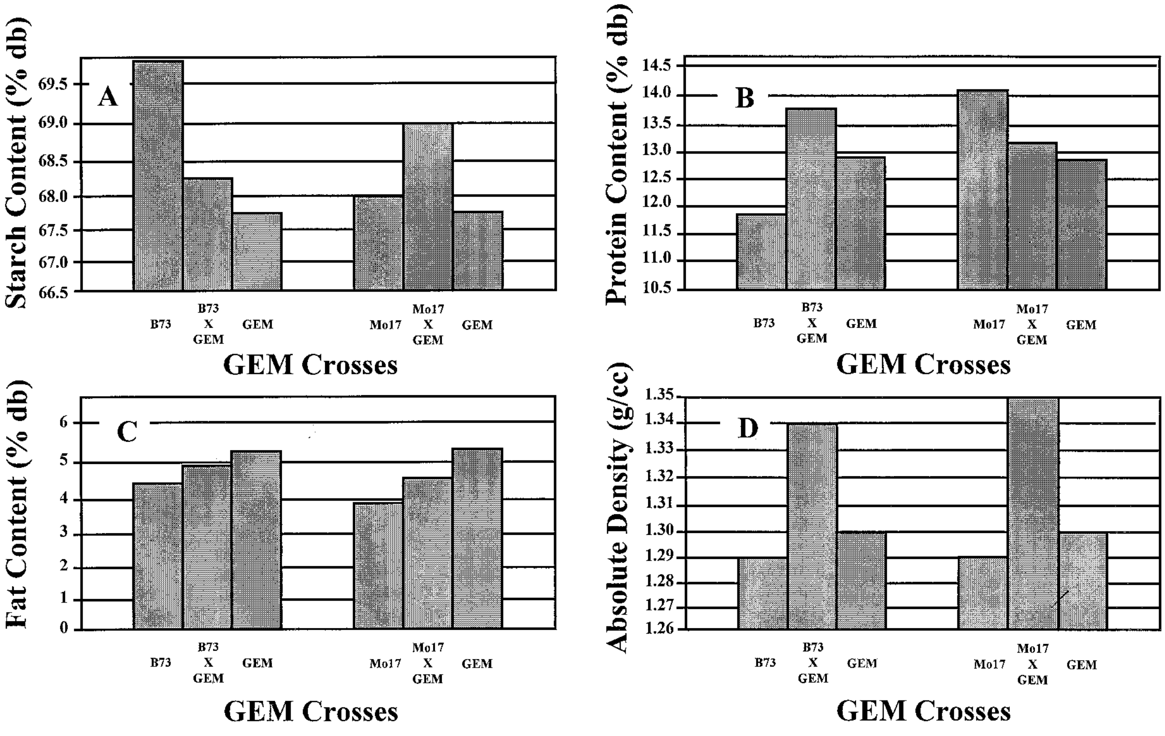

Fig. 1. Mean expressions of heterosis for compositional and physical properties of Germplasm Enhancement of Maize project crosses. **A,** starch content; **B,** protein content; **C,** fat content; **D,** absolute density. Numbers on x-axis arecenter points for the column.

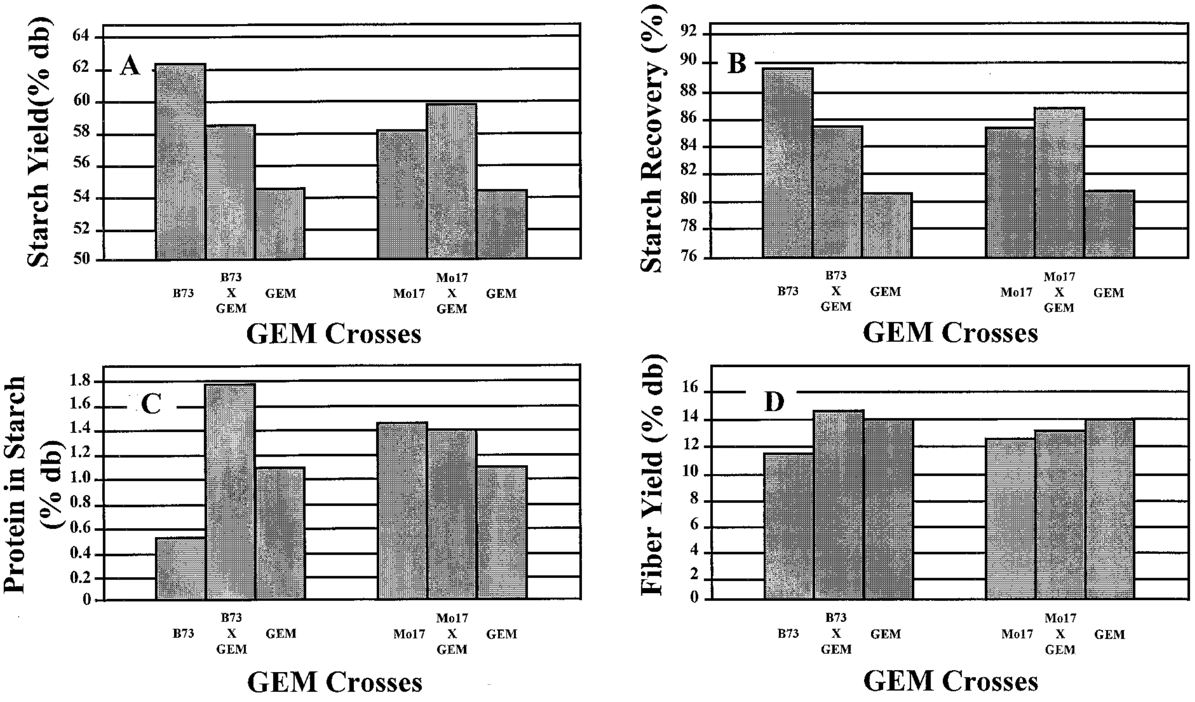

Fig. 2. Mean expressions of heterosis for wet-milling properties of Germplasm Enhancement of Maize project crosses. **A,** starch yield; **B,** starch recovery; **C,** protein in starch; **D,** fiber yields. Numbers on x-axis arecenter points for the column.

Despite B73 as a parent producing lower fiber yields than did Mo17, the GEM × B73 crosses resulted in greater fiber yields than did the GEM × Mo17 crosses. Poor fiber-washing characteristics of the GEM × B73 crosses were attributed to the higher protein content of the grain. The 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).

TABLE IV

Midparent Heterosis in Compositional, Physical, and Wet-Milling Properties of GEM × B73 and GEM × Mo17 Crosses[a,b]

	Compositional			Physical			Wet Milling[c]								
Cross	**Str**	**Pro**	**Fat**	**TWt**	**KWt**	**ADen**	**StrY**	**PiS**	**SRec**	**Glu**	**PiG**	**Germ**	**Fib**	**SW**	**Fil**
GEM × B73 Crosses															
CHZM 05015 × 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 × 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 × 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 × 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 × 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
Guatemala 209 × 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 × 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 × 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) × B73	–2.6	12.7	16.8	2.0	–12.2	3.1	0.0	274.1	2.7	7.7	–2.5	14.0	12.7	11.4	–34.9
FS8A(T) × B73	–1.8	9.9	13.1	0.9	–5.6	1.9	2.1	–42.0	4.0	14.1	–4.4	7.5	2.0	12.2	–38.1
Mean	–0.5	10.4	2.9	0.5	–8.3	2.7	0.7	129.5	1.3	0.4	1.1	7.5	13.8	13.1	–31.8
GEM × Mo17 Crosses															
CHZM 05015 × 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 × 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 × 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 × 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 × 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
Guatemala 209 × 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 × 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 × 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) × 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
S8A(T) × 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	–0.1	–34.1

[a] GEM = Germplasm Enhancement of Maize Project, Str = starch content, Pro = protein content, Fat = crude free fat content, TWt = test weight (lb/bu), KWt = thousand-kernel weight (g), ADen = absolute density (g/cm^3), StrY = starch yield, PiS = protein in starch, SRec = starch recovery, Glu = gluten yield, PiG = protein in gluten, Germ = germ yield, Fib = fiber yield, SW = steepwater solids yield, and Fil = filtrate solids yield.

[b] Compositional and wet-milling properties are reported as %db. All physical properties are reported on 15% moisture basis.

[c] Indicated as %db, except SRec as %.

TABLE V

High-Parent Heterosis in Compositional, Physical, and Wet-Milling Properties of B73 × GEM and Mo17 × GEM Crosses[a,b]

	Compositional			Physical			Wet Milling[c]								
Cross	**Str**	**Pro**	**Fat**	**TWt**	**KWt**	**ADen**	**StrY**	**PiS**	**SRec**	**Glu**	**PiG**	**Germ**	**Fib**	**SW**	**Fil**
GEM × B73 Crosses															
CHZM 05015 × 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 × 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 × 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 × 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 × 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
Guatemala 209 × 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 × 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 × 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) × 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) × 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 × Mo17 Crosses															
CHZM 05015 × 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 × 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 × 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 × 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 × 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
Guatemala 209 × 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 × 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 × 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) × 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
S8A(T) × 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] GEM = Germplasm Enhancement of Maize Project, Str = starch content, Pro = protein content, Fat = crude free fat content, TWt = test weight (lb/bu), KWt = thousand-kernel weight (g), ADen = absolute density (g/cm^3), StrY = starch yield, PiS = protein in starch, SRec = starch recovery, Glu = gluten yield, PiG = protein in gluten, Germ = germ yield, Fib = fiber yield, SW = steepwater solids yield, and Fil = filtrate solids yield.

[b] Compositional and wet-milling properties are reported as %db. All physical properties are reported on 15% moisture basis.

[c] Indicated as %db, except SRec as %.

The GEM × Corn Belt inbred crosses yielded more germ than did the GEM accessions (a mean of 5.4% for the GEM × B73 crosses and a mean of 6.7% for the GEM × Mo17 crosses vs. 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 the GEM accessions (means of 4.8% for the GEM × B73 crosses and 4.7% for the GEM × Mo17 crosses vs. a mean of 4.5% for the GEM accessions). Despite B73 (4.0%) as a parent yielding lower steepwater solids than Mo17 (4.9%), the GEM × B73 crosses resulted in greater steepwater solids yields, which we attributed to the greater protein contents of the GEM × B73 crosses.

Filtrate solids yields for the GEM × Corn Belt inbred crosses were lower than either of the parents (means of 2.9% for the GEM × B73 and 2.6% for the GEM × Mo17 crosses vs. 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 improved wet-milling performance of the crosses.

The GEM × B73 crosses exhibited additive effects for grain protein content and fiber yield, which are not desirable characteristics for wet milling. The GEM × 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 milling. Zehr et al (1995) have made similar observations. Although Mo17 as a parent possessed inferior wet-milling properties compared with B73, it produced crosses with superior properties.

Midparent Heterosis

Midparent heterosis was greater in the GEM × Mo17 crosses for absolute density, test weight, and 1,000-kernel weight than in the GEM × B73 crosses (3.5, 5.1, and 23.0% for the GEM × Mo17 crosses vs. 2.7, 0.46, and –8.3% for the GEM × B73 crosses, respectively) (Table IV). Midparent heterosis in the GEM × Mo17 crosses was greater for starch content (1.68% for the GEM × Mo17 crosses vs. –0.45% for the GEM × B73 crosses), but lower for protein and fat contents (–2.7 and 2.4% for the GEM × Mo17 crosses vs. 10.4 and 2.9% for the GEM × B73 crosses, respectively).

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

High-Parent Heterosis

High-parent heterosis was greater in the GEM × Mo17 crosses for absolute density, test weight, and 1,000-kernel weight than in the GEM × B73 crosses (1.44, 1.92, and 7.99% for the GEM × Mo17 crosses vs. 0.91, –0.56, and –16.01% for the GEM × B73 crosses, respectively) (Table V). High-parent heterosis in the GEM × Mo17 crosses was greater for starch content (1.13% for the GEM × Mo17 crosses vs. –1.99% for the GEM × B73 crosses), but lower for protein and fat contents (–6.82 and –8.91 for the GEM × Mo17 crosses vs. 6.78 and –5.02 for the GEM × B73 crosses, respectively).

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

CONCLUSIONS

The grain of the GEM accessions contained more protein and oil, was denser, and possessed much poorer wet-milling properties than did 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 five percentage points, but were still at least five percentage points less than typical of commercial Dent hybrids. The residual protein contents of the starches recovered from the crosses were also extraordinarily high (a mean of >1.5%) and unacceptable from an industry perspective; however, 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 as compared with B73, which had better wet-milling properties as an inbred. Because Mo17 belongs to the non-Stiff Stalk heterotic pattern, breeders using 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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