Dry-Milling Properties of Maize

C. MESTRES, A. LOUIS-ALEXANDRE, F. MATENCIO, and A. LAHLOU[1]

ABSTRACT

Cereal Chem. 68(1):51-56

Chemical composition and physical properties of 18 African maize samples were determined and correlated with their dry-milling performance. Semolina yield could be predicted (at almost 60%) from ash content (main factor, correlation coefficient −0.64) and sphericity or dent kernel percentage (cofactors). Vitreousness was not significantly correlated (at the 0.05 level) with semolina yield. Vitreousness, which was very time-consuming to measure, could be evaluated at almost 90% from density and dent kernel percentage or ash content. Lipid content of recovered semolinas was also positively correlated with kernel ash content. Thus, maize varieties with low ash content gave high yields of semolina with low lipid content.

In developing countries, maize (*Zea mays* L.) is mainly used for human consumption. In Africa, maize ears are eaten boiled or roasted, but shelled maize is also milled to flour or semolinas, which are used to make couscous (Senegal, Mali, Togo), porridges, or pastes (*akoumé* in Togo, *akassa* in the Ivory Coast and Benin, and *agidi* in Nigeria). Maize consumption is increasing in developing countries of Africa, and breeding programs have been launched to develop high-performance varieties. But the new varieties have been bred to show increased field yields rather than better kernel quality in terms of technological, organoleptic, and nutritional properties. The exceptions are QPM varieties, which were developed for their protein and amino acid composition.

Similarly, most maize varieties in developed countries, except sweet maize and pop maize, were not bred for their kernel quality. Furthermore, no quality criterion is universally recognized by the processors and end users of maize. For example, U.S. maize standards are based mainly on purity and integrity ("broken corn and foreign material") (Gunasekaran 1988). Test weight is also used as a grading factor for trading. Although test weight is correlated with dry- and wet-milling performance of maize, end users have developed their own quality tests (Watson 1987b).

Because U.S. maize may be handled as many as 20 times from harvest to export (Miller et al 1981), maize traders prefer varieties that are resistant to breakage during handling. Therefore, many tests have been developed to evaluate kernel hardness, or resistance to breakage. Two types of mechanical breakage tests have been proposed. One type uses the impact of a moving blade (e.g., the Stein breakage tester); the other type uses centrifugal impact of individual kernels against a stationary surface (e.g., the Wisconsin breakage tester). AACC Method 55-20 (AACC 1983) describes the use of the Stein breakage tester under specific conditions, but there is no widely used, standardized method (Gunasekaran 1988). Furthermore, numerous indirect tests for breakage susceptibility and hardness have been developed, including visual estimation of horny-floury ratio; kernel density (real density or floating test); work required to grind a sample in a laboratory

---

[1] CIRAD-IRAT, Laboratoire de Technologie des Céréales, 2 Place Viala, 34060 Montpellier Cedex 1, France.

hammer mill; grinding resistance (maximum torque necessary to crush individual kernels under compression); average particle size (APS) resulting from grinding, measured by sieving ground kernels or evaluated by near-infrared reflectance (NIR) of milled product at 1,680 nm (Jindal et al 1979; Tran et al 1981; Paulsen et al 1983; Pomeranz et al 1984, 1985; Watson and Herum 1986; Watson et al 1986; Gunasekaran 1988).

Far fewer tests are available for predicting the industrial behavior of maize during its end uses, such as production of brewery grits. Feillet and Redon (1975), Peplinski et al (1989), and Stroshine et al (1986) proposed dry-milling tests using 3–6 kg of raw material. Postharvest conditions (drying, infestation) largely governed grits recovery (Brekke et al 1972, Feillet and Redon 1975, Peplinski et al 1989), which also appeared to be influenced by inheritable kernel characteristics such as density, test weight, horny-floury endosperm ratio, and NIR spectroscopy of ground kernels at 1,680 nm (Manoharkumar et al 1978, Paulsen and Hill 1985, Stroshine et al 1986, Pomeranz and Czuchajowska 1987).

Vitreousness is commonly associated with hardness and dry-milling behavior (Paulsen et al 1983; Paulsen and Hill 1985; Watson 1987a,b), but a clear relationship does not always hold (Abdelrahman and Hoseney 1984, Fliedel et al 1989), perhaps because vitreousness is not known with sufficient precision. For example, Paulsen et al (1983) estimated vitreousness by visual examination of endosperm from cross sections of only 10 kernels, despite the great variability they observed within samples. Furthermore, dent maizes are generally considered semifloury and "soft" (Wolf et al 1952).

Thus, no single chemical or physical (vitreousness, hardness) test is currently used to predict end-use quality of maize varieties. A very recent trend in developed countries is to try to adapt maize varieties to their end uses and to breed new varieties not only for their agronomic performance but also for their technological properties (Stroshine et al 1986, Peplinski et al 1989). Such approaches are also beginning to emerge in developing countries.

As a first contribution in this field, the research reported here attempted to characterize West African maize varieties first in terms of the physicochemical properties of their kernels and second in terms of their dry-milling behavior (because milling is the first step in and a necessary part of maize processing). We then correlated dry-milling responses and physicochemical properties in an attempt to develop some technological breeding tests.

TABLE I
Proximate Analysis of Whole Maize Kernels

Variety	Country of Origin	Protein[a] (% db)	Lipid[a] (% db)	Ash[a] (% db)
Ikenne	Togo	9.5 ef	5.00 b	1.13 e
Poza Rica	Togo	8.4 g	4.90 b	1.21 e
La Posta	Togo	9.1 fg	4.60 cd	1.17 e
B.S.R.	Cameroon	9.9 de	5.00 b	1.47 b
Local	Togo	9.1 fg	3.60 f	1.55 a
NH1 F2	Togo	7.4 h	4.50 cd	1.23 de
Pirsabak-SR	Togo	8.6 g	4.90 b	1.28 cde
Tuxpenio	Senegal	9.6 ef	4.50 cd	1.14 e
Thiementie	Senegal	9.8 de	4.00 e	1.35 cd
Mexico	Togo	10.1 cde	4.15 e	0.96 f
NH1 F1[b]	Togo	8.1 g	4.20 de	1.39 bc
Synthetic C	Senegal	10.4 cd	4.20 de	1.16 e
Camara 1	Senegal	9.6 ef	4.30 de	1.23 de
Q.P.M.	Senegal	12.3 a	4.55 cd	1.26 cde
Nzazaka	Congo Republic	10.1 cde	3.70 f	1.61 a
Tzesr-W	Congo Republic	11.3 b	5.80 a	1.51 ab
NH1 F1[b]	Togo	10.2 cde	5.00 b	1.52 ab
Jaune de Bambey	Senegal	10.7 c	4.75 bc	1.51 ab
Minimum		7.4	3.7	0.96
Maximum		12.3	5.8	1.61
CV[c]		2.4	2.4	2.9
LSD[c]		0.5	0.25	0.1

[a] Different letters denote statistically significant differences at the 0.05 level.

[b] The two NH1 F1 samples were grown in different locations.

[c] Coefficient of variation (CV) and least significant difference (LSD) between two samples at $P < 0.05$ obtained from one-way analysis of variance across the 18 maize samples.

MATERIALS AND METHODS

Maize

Samples (10–100 kg) of 17 yellow and white maize varieties were collected in 1987 and 1988 from several African countries (Senegal, Togo, Cameroon, and the Congo Republic) (Table I). The variety NH1 F1 was harvested in two locations. Each sample was dried in situ at ambient air temperature (25–35°C). Final moisture content ranged from 11 to 13.5% (wb). Maize was stored at 4°C and brought up to 25°C one day before the tests were performed.

Chemical Analysis

Whole maize was ground to pass through a 0.5-mm sieve. Ground samples (5 g) were used for the determination of dry matter (residue weighed after heating at 130°C for 2 hr), ash content (residue weighed after calcination at 900°C for 2 hr), and lipid content (extract weighed after extraction in boiling ethyl ether for 20 min and distillation of the solvent). Nitrogen content was determined by a semiautomatic method (Feillet 1976) on 1 g of the ground samples. All chemical analyses were performed in duplicate.

Physical Analysis

All tests for physical analysis were done on maize that had been stored for two weeks in an air-conditioned room (20°C, 65% rh) in order to equilibrate the grain to 12.5 ± 1% moisture (wb). The percentage of dent kernels (DKP) was determined by visual examination of three populations of 50 kernels. Thousand-kernel weight was measured in duplicate with an automatic kernel counter (Chopin, Villeneuve la Garenne, France) on 30-g samples; the results were expressed as dry matter.

Sphericity was calculated from measurements of the three dimensions of 50 maize kernels (measured with a gauge at a precision of 0.1 mm), as described by Pomeranz et al (1985). The closer to unity the sphericity, the more spherical (or isotropic) the kernel; conversely, the lower the sphericity, the flatter (or anisotropic) the kernel.

Kernel density was determined with a helium-comparison pycnometer, as described by Chang (1988). The volume of maize samples weighing 35–40 g was measured in the air-conditioned room (20°C, 65% rh), and density was calculated from the ratio of mass to volume. Three replicates were tested for each variety.

Vitreousness was evaluated on 50 maize grains. Cross sections of kernels were photographed and enhanced seven times, and areas of horny and total endosperm were measured using a digitization table. The standard deviation for area measurement was less than 1%. Vitreousness (expressed as a percentage) was calculated as the mean value of the ratio of horny to total endosperm area.

Dry Milling

Dry milling was performed on a roller mill (Mestres et al 1990) on samples weighing 4–5 kg, without use of a degerminator (Feillet and Redon 1975). Regular grits (particle diameter above 750 μm) were extracted, then purified through a reduction step. Obtained semolinas (fine grits with particles 290–400 μm in diameter) and flours (particle diameter below 290 μm) were collected and weighed. Semolina and flour recoveries (addition of degerming and reduction products) were expressed as percentages of the initial maize grains. Reduction semolinas were analyzed for their chemical composition, as described already for whole kernels.

RESULTS AND DISCUSSION

Proximate analyses of whole kernels of the 18 maize samples are presented in Table I. Varieties varied considerably in protein (7.4–12.3%), lipid (3.7–5.8%), and ash (0.96–1.61%) content. These ranges were far broader than those observed for dent and flint maize hybrids in developed countries (Pomeranz et al 1985, Pomeranz and Czuchajowska 1987, Peplinski et al 1989). Coefficients of variation between duplicates were below 3%. Five, six, and seven homogeneous subgroups could be identified within the total group of 18 samples for ash, lipid, and protein content, respectively.

Physical properties of whole kernels are reported in Table II. As with chemical composition, wide ranges of measurements were observed among varieties. For instance, vitreousness ranged from 6% for Nzazaka to 80% for La Posta. But great variations were also observed within varieties. The coefficients of variation for sphericity and vitreousness were 10.6 and 34.1%, respectively. This variability reflected the very high heterogeneity of individual kernels within the samples. Furthermore, even 1,000-kernel weights and DKPs, which were measured on grain populations weighing 30 g (i.e., 120–150 kernels) and on samples of 50 kernels, respectively, showed relatively high coefficients of variation compared to those observed for chemical analyses (Table II), even though the latter analyses were done on samples of only 5 g. Only the density measurements (measured on 30-g samples) appeared very reproducible. Thus, heterogeneity within varieties mainly concerned the physical characteristics of the kernels (with the exception of their density) and not their chemical composition. These results are consistent with the literature: maize kernels are known to be heterogeneous within a variety and even on the same ear (Wolf et al 1952). For example, Pomeranz et al (1985) and Watson (1987a) showed that maize hybrids could be separated into subgroups with sphericity from 0.65 to 0.84 and that kernels exhibited great ranges of horny and floury endosperm fraction.

Nevertheless, the physical characteristics of kernels were determined with sufficient precision to distinguish five to seven homogeneous groups of varieties at the 0.05 level of significance. For example, with 50 replicates the least significant differences at $P < 0.05$ were 0.05 for sphericity and 7% for vitreousness (Table II).

The two NH1 F1 populations (grown at different locations) had very similar physical characteristics, whereas their chemical compositions were significantly different (Table I). This result was surprising because Hamilton et al (1951) demonstrated that soil fertility not only affects the chemical composition of maize kernels but also modifies their 1,000-kernel weight and vitreousness.

Semolina and flour recoveries for the 18 maize samples are reported in Table III. Semolina recovery ranged from 40 to 61%, and flour recovery ranged from 7 to 30%. The most floury maizes were the NH1 F1 samples regardless of growing location.

Proximate analyses of maize reduction semolinas are also reported in Table III. Protein content was low compared to that of whole kernels (Table I). On the other hand, semolina free

TABLE III
Dry-Milling Behavior of Maize Varieties:
Semolina and Flour Recoveries and Proximate Analysis
of Reduction Semolinas

	Recovery (%)		Semolina Composition (% db)		
Variety	Semolina	Flour	Protein	Lipid	Ash
Ikenne	50	10	8.3	1.5	0.53
Poza Rica	48	14	7.5	1.1	0.38
La Posta	55	10	7.6	0.8	0.21
B.S.R.	48	15	9.8	1.3	0.21
Local	51	16	9.1	0.9	0.27
NH1 F2	53	15	9.0	1.0	0.37
Pirsabak-SR	60	11	7.0	0.8	0.29
Tuxpenio	60	9	8.8	0.8	0.37
Thiementie	48	9	8.2	1.1	0.35
Mexico	57	12	9.0	0.7	0.28
NH1 F1[a]	42	27	7.4	0.9	0.42
Synthetic C	60	20	11.8	1.6	0.47
Camara 1	56	12	8.8	0.7	0.42
Q.P.M.	61	11	10.6	1.1	0.38
Nzazaka	40	20	11.0	1.6	0.67
Tzesr-W	48	7	10.7	1.5	0.49
NH1 F1[a]	40	30	11.0	1.3	0.54
Jaune de Bambey	54	12	10.2	2.0	0.56
Minimum	40	7	7.0	0.7	0.21
Maximum	61	30	11.8	2.0	0.67

[a] The two NH1 F1 samples were grown in different locations.

TABLE II
Physical Characteristics of Whole Maize Kernels

Variety	1,000-Kernel Weight[a] (g)	Dent Kernel Percentage[a]	Sphericity[a]	Vitreousness[a] (%)	Density[a] (g/cm^3)
Ikenne	193 cde	61 a	0.70 cde	68 bc	1.32 c
Poza Rica	218 bc	51 ab	0.65 e	44 f	1.29 f
La Posta	213 bcd	61 a	0.74 bcd	80 a	1.33 c
B.S.R.	207 bcde	47 b	0.65 e	10 h	1.17 h
Local	160 g	11 cde	0.80 ab	20 g	1.25 g
NH1 F2	183 ef	23 c	0.73 bcd	56 de	1.26 g
Pirsabak-SR	194 cde	3 e	0.74 bcd	54 de	1.31 cde
Tuxpenio	194 cde	20 cd	0.73 bcd	65 cd	1.33 c
Thiementie	181 ef	4 de	0.76 bc	56 de	1.34 b
Mexico	153 g	45 b	0.69 cde	76 ab	1.33 c
NH1 F1[b]	177 f	12 cde	0.74 bcd	58 de	1.30 ef
Synthetic C	240 a	0 c	0.76 bc	57 de	1.32 cd
Camara 1	211 bcd	20 cd	0.74 bcd	68 bc	1.33 c
Q.P.M.	192 cdef	13 cde	0.82 a	54 de	1.30 ef
Nzazaka	191 def	45 b	0.73 bcd	6 h	1.16 h
Tzesr-W	205 bcdef	2 c	0.71 cde	74 abc	1.36 a
NH1 F1[b]	179 f	20 cd	0.71 cde	49 ef	1.31 cde
Jaune de Bambey	224 b	16 cde	0.74 bcd	75 abc	1.35 ab
Minimum	153	0	0.65	6	1.16
Maximum	240	61	0.82	80	1.36
CV[c]	3.8	23	10.6	34.1	0.5
LSD[c]	16	11	0.05	7	0.01

[a] Different letters denote statistically significant differences at the 0.05 level.

[b] The two NH1 F1 samples were grown in different locations.

[c] Coefficient of variation (CV) and least significant difference (LSD) between two samples at $P < 0.05$ obtained from one-way analysis of variance across the 18 maize samples.

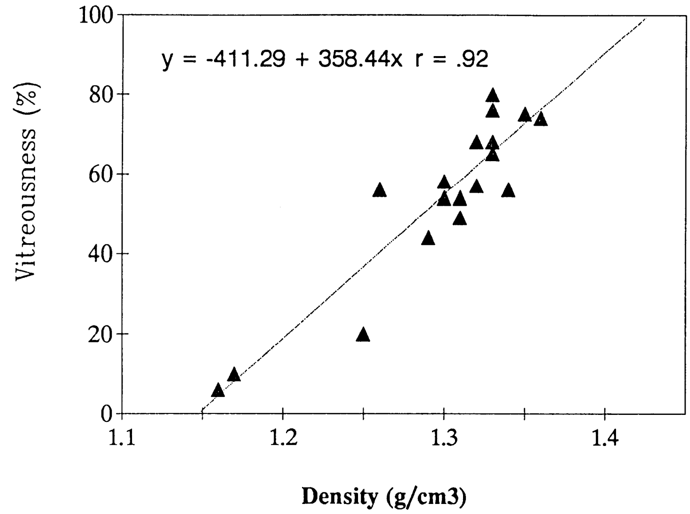

Fig. 1. Correlation between vitreousness and density of whole maize kernels.

lipid content was between 0.7 and 2.0%, and ash content was below 0.7%.

Vitreousness was significantly correlated with ash content and even more so with density (Table IV and Fig. 1). Multifactorial regression analysis showed that vitreousness could be predicted at 88% from density and ash content (Table V). (Note that the regression was very similar when the three floury varieties [B.S.R., Local, and Nzazaka] were excluded.) Density and DKP also predicted vitreousness very accurately (Table V), although DKP was not simply correlated with vitreousness (Table IV). Thus, it did not appear that a flint kernel is not indented, as Wolf et al (1952) reported. The variety La Posta provided an obvious exception to this statement: its vitreousness and DKP were the highest of the 18 samples. On the contrary, the regression coefficient between DKP and vitreousness was weakly positive, which meant that, with equivalent density, the more dent kernels that were present, the more horny they were. This result was very surprising and must be confirmed on more varieties. Furthermore, vitreousness is also measured on longitudinal cross sections of kernels parallel or perpendicular to germ front (Watson 1987a).

Lipid content was negatively correlated with sphericity: when

TABLE IV

Simple Correlation Coefficients Between Chemical Composition and Physical Properties of Whole Maize Kernels

	Protein	Lipid	Ash	1,000-Kernel Weight	Dent Kernel Percentage (DKP)	Sphericity	Density
Lipid	0.16	1					
Ash	0.18	−0.01	1				
1,000-Kernel weight	0.19	0.34	−0.03	1			
DKP	−0.20	0.07	−0.28	0.00	1		
Sphericity	0.27	−0.50*[a]	0.12	−0.14	−0.58**	1	
Density	0.18	0.30	−0.43	0.14	−0.33	0.18	1
Vitreousness	0.08	0.32	−0.57**	0.16	−0.10	0.07	0.92**

[a] One asterisk indicates significance at the 0.05 level; two asterisks indicate significance at the 0.01 level.

TABLE V

Linear Regression Equations and Standard Error of Estimates of Vitreousness, Semolina Yield, and Lipid Content of Semolinas

		Whole-Kernel Characteristics					
Equation	Constant	Ash	1,000-Kernel Weight	Dent Kernel Percentage	Sphericity	Density	Coefficient of Determination
Vitreousness							
Regression coefficient	−456			0.25		388	0.89
Standard error of estimate				0.10		35	
Vitreousness							
Regression coefficient	−328	−27				322	0.88
Standard error of estimate		12				38	
Semolina recovery							
Regression coefficient	36	−26			69		0.60
Standard error of estimate		6			26		
Semolina recovery							
Regression coefficient	92	−28		−0.13			0.56
Standard error of estimate		6.7		0.06			
Semolina lipid content							
Regression coefficient	−1.78	1.0	0.008				0.47
Standard error of estimate		0.4	0.003				

TABLE VI

Simple Correlation Coefficients Between Whole-Kernel Characteristics and Dry-Milling Behavior

	Whole-Kernel Characteristics								
Dry-Milling Performance	Protein	Lipid	Ash	1,000-Kernel Weight	DKP[a]	Sphericity	Density	Vitreousness	Semolina Yield
Milling yield									
Semolina	0.17	−0.03	−0.64**[b]	0.25	−0.19	0.36	0.40	0.44	
Flour	−0.21	−0.23	0.37	−0.16	−0.08	−0.04	−0.36	−0.40	−0.58**
Semolina composition									
Protein	0.70**	0.00	0.38	0.23	−0.25	0.17	−0.18	−0.23	−0.03
Lipid	0.43	0.20	0.49*	0.46*	−0.03	−0.12	−0.10	−0.13	−0.31
Ash	0.29	0.01	0.38	0.20	−0.09	0.02	−0.02	−0.05	−0.42

[a] Dent kernel percentage.

[b] One asterisk indicates significance at the 0.05 level; two asterisks indicate significance at the 0.01 level.

the germ was large, lipid content was high, and the kernel was flat (low sphericity). Sphericity and DKP were highly significantly and negatively correlated: to a first approximation, dent kernels were flat.

Semolina recovery was highly and negatively correlated with ash content of whole kernels (Table VI). Multifactorial regression analysis showed that ash content and sphericity (or DKP, since these two variables were correlated) explained 56–60% (coefficients of determination, Table V) of the semolina recovery.

Vitreousness was not significantly correlated ($P < 0.05$) with semolina recovery. The correlation coefficient (0.44) was significant only at the 0.1 level. Protein content of whole kernels and semolina yield were not significantly correlated (Table VI). Pomeranz and Czuchajowska (1987) showed that recovery of flaking grits after dry milling was highly correlated with hardness. Grits recovery can be considered as a hardness factor, like APS or NIR at 1,680 nm observed after grinding. Thus, our results contradict the general idea that vitreousness is associated with kernel hardness, protein content, and dry-milling response (Paulsen et al 1983, Paulsen and Hill 1985, Abdelrahman and Hoseney 1984) but agree with results of Fliedel et al (1989), who demonstrated that sorghum hardness was not correlated with kernel vitreousness or protein content. Only a part of kernel proteins, those soluble in 60% *tert*-butanol, appeared linked to hardness of sorghum and maize (Fliedel et al 1989, Abdelrahman and Hoseney 1984).

Average semolina composition was not correlated with semolina recovery (Table VI). Protein content of the reduction semolinas was highly correlated with kernel protein content, whereas semolina lipid content was correlated with kernel ash content and 1,000-kernel weight. These results do not agree with those of Pomeranz and Czuchajowska (1987), who found that lipid and ash contents of flaking grits were correlated with grits recovery and kernel density, respectively. These authors studied only seven maize varieties with a density range of only 0.05 g/cm^3, compared to a density range of 0.20 g/cm^3 in our study. The relationship found for relatively homogeneous varieties should not be extrapolated to very heterogeneous varieties like those studied here.

Flour recovery was not correlated with any chemical or physical kernel characteristic, although it was negatively correlated with semolina yield. The dry-milling pilot method, optimized to produce semolinas, was not very appropriate for the extraction of flour (the sieving was not effective enough), which could explain the low reproducibility we obtained for flour recovery and thus the absence of significant correlation.

CONCLUSION

We found a great range of chemical compositions and physical properties among the 18 African maize samples. Vitreousness, for instance, which was measured quantitatively, ranged from 6 to 80%. Variability was also important within samples, especially with regard to the physical properties (except density).

Our results show that vitreousness, which was very time-consuming to measure, could be predicted (at almost 90%) from density and DKP or kernel ash content. Furthermore, DKP was not simply correlated with vitreousness but seemed to be positively associated with it at equivalent kernel density, contrary to the assertion that a dent maize is floury. Finally, kernel protein content was not highly correlated with vitreousness. Further studies on maize vitreousness and the role of specific proteins in its determination are in progress.

Nevertheless, vitreousness was not relevant for the prediction of dry-milling performance of maize; that is, it was not significantly correlated (at the 0.05 level) with semolina recovery. Kernel ash content and sphericity (or DKP) explained almost 60% of the variation in semolina yield; the lower the ash content, the greater the semolina yield.

Protein content of the semolinas was highly correlated with the initial protein content of the kernel, whereas the lipid content of the semolinas was positively correlated with the kernel ash content. Thus, maize that is high in protein and low in ash should give high semolina recovery with high protein content but low lipid content.

Simple chemical (ash and protein content) and physical (sphericity or DKP) criteria could predict dry-milling performance (semolina quantity and quality) of maize lots. These criteria must be confirmed by tests with other maize samples and explained. For instance, further research is needed to establish whether ash content plays a direct role in semolina recovery or is simply linked to another functional factor. Furthermore, we do not yet know whether these criteria are inherited or controlled by environmental factors. Only if they are mainly genetically controlled should they be used for breeding tests of maize varieties.

LITERATURE CITED

AMERICAN ASSOCIATION OF CEREAL CHEMISTS. 1983. Approved Methods of the AACC, 8th ed. Method 55-20, approved November 1981. The Association: St. Paul, MN.

ABDELRAHMAN, A. A., and HOSENEY, R. C. 1984. Basis for hardness in pearl millet, grain sorghum, and corn. Cereal Chem. 61:232-235.

BREKKE, O. L., PEPLINSKI, A. J., GRIFFIN, E. L., JR., and ELLIS, J. J. 1972. Dry-milling of corn attacked by Southern leaf blight. Cereal Chem. 49:466-478.

CHANG, C. S. 1988. Measuring density and porosity of grain kernels using a gas pycnometer. Cereal Chem. 65:13-15.

FEILLET, P. 1976. Dosage semi-automatique de la teneur en protéines des céréales par la méthode Kjeldahl. Tech. Ind. Cerealieres 153:17.

FEILLET, P., and REDON, C. 1975. Etude préliminaire de quelques facteurs de la valeur semoulière du maïs. Bull. ENSMIC 270:325-330.

FLIEDEL, G., GRENET, C., GONTARD, N., and PONS, B. 1989. Dureté, caractéristiques physicochimiques et aptitude au décorticage des grains de sorgho. Pages 187-210 in: Proceedings of "Céréales Régions Chaudes: Conservation et Transformation." M. Parmentier and K. Fouabi, eds. AUPELF/UREF, J. Libbey Eurotext: Paris.

GUNASEKARAN, S. 1988. Evaluation and comparison of Wisconsin and Stein breakage testers on corn. Cereal Chem. 65:287-291.

HAMILTON, T. S., HAMILTON, B. C., JOHNSON, B. C., and MITCHELL, H. H. 1951. The dependence of the physical and chemical composition of the corn kernel on soil fertility and cropping system. Cereal Chem. 28:163-176.

JINDAL, V. K., HERUM, F. L., and HAMDY, M. Y. 1979. Selected breakage characteristics of corn. Trans. ASAE 22:1193-1196.

MANOHARKUMAR, B., GERSTENKORN, P., ZWINGELBERG, H., and BOLLING, H. 1978. On some correlations between grain composition and physical characteristics to the dry milling performance in maize. J. Food Sci. Technol. 15:1-6.

MESTRES, C., MATENCIO, F., and FAURE, J. 1990. Optimising process for making pasta from maize in admixture with durum wheat. J. Sci. Food Agric. 51:355-368.

MILLER, B. S., HUGHES, J. W., ROUSSER, R., and POMERANZ, Y. 1981. Measuring the breakage susceptibility of shelled corn. Cereal Foods World 26:75-80.

PAULSEN, M. R., and HILL, L. D. 1985. Corn quality factors affecting dry milling performance. J. Agric. Eng. Res. 31:255-263.

PAULSEN, M. R., HILL, L. D., WHITE, D. G., and SPRAGUE, G. F. 1983. Breakage susceptibility of corn-belt genotypes. Trans. ASAE 26:1830-1836, 1841.

PEPLINSKI, A. J., PAULSEN, M. R., ANDERSON, R. A., and KWOLEK, W. F. 1989. Physical, chemical, and dry-milling characteristics of corn hybrids from various genotypes. Cereal Chem. 66:117-120.

POMERANZ, Y., and CZUCHAJOWSKA, Z. 1987. Laboratory tests to predict the commercial yield of flaking or large grits in dry corn milling. J. Food Sci. 52:830, 832.

POMERANZ, Y., MARTIN, C. R., TRAYLOR, D. D., and LAI, F. S. 1984. Corn hardness determination. Cereal Chem. 61:147-150.

POMERANZ, Y., CZUCHAJOWSKA, Z., MARTIN, C. R., and LAI, F. S. 1985. Determination of corn hardness by the Stenvert hardness tester. Cereal Chem. 62:108-112.

STROSHINE, R. L., KIRLEIS, A. W., TUITE, J. F., BAUMAN, L. F., and EMAM, A. 1986. Differences in grain quality among selected corn hybrids. Cereal Foods World 31:311-316.

TRAN, T. L., deMAN, J. M., and RASPER, V. F. 1981. Measurement of corn kernel hardness. Can. Inst. Food Sci. Technol. J. 14:42-48.

WATSON, S. A. 1987a. Structure and composition. Pages 53-82 in: Corn: Chemistry and Technology. S. A. Watson and P. E. Ramstad, eds. Am. Assoc. Cereal Chem.: St. Paul, MN.

WATSON, S. A. 1987b. Measurement and maintenance of quality. Pages 125-183 in: Corn: Chemistry and Technology. S. A. Watson and P. E. Ramstad, eds. Am. Assoc. Cereal Chem.: St Paul, MN.

WATSON, S. A., and HERUM, F. L. 1986. Comparison of eight devices for measuring breakage susceptibility of shelled corn. Cereal Chem. 63:139-142.

WATSON, S. A., DARRAH, L. L., and HERUM, F. L. 1986. Measurement of corn breakage susceptibility with the Stein breakage tester: A collaborative study. Cereal Foods World 31:366-372.

WOLF, M. J., BUZAN, C. L., MacMASTERS, M. M., and RIST, C. E. 1952. Structure of the mature corn kernel. I. Gross anatomy and structural relationships. Cereal Chem. 29:321-332.

[Received January 31, 1990. Revision received July 8, 1990. Accepted July 8, 1990.]