Relationships between Simple Grain Quality Parameters for the Estimation of Sorghum and Maize Hardness in Commercial Hybrid Cultivars

Constance Chiremba,[1,3] Lloyd W. Rooney,[1,4] and John R. N. Taylor[1*]

[1] Department of Food Science, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa

[2]Cereal Quality Laboratory, Department of Soil and Crop Sciences, Texas A&M University, College Station, Texas 77843-2474, USA

[3]Agricultural Research Council-Grain Crops Institute, Potchefstroom, 2520, South Africa

[4]Extraordinary Professor, Department of Food Science, University of Pretoria

* Corresponding author. E-mail address: john.taylor@up.ac.za: Phone: +27 124204296

ABSTRACT

Grain hardness affects sorghum and maize processing properties especially for dry milling. A variety of simple grain quality parameters were assessed on seventeen sorghum, and thirty-five white maize hybrid cultivars grown in six and four locations, respectively, in South Africa. The purpose was to determine tests that can be used to distinguish hardness in commercial sorghum and maize. The grains were characterized by test weight (TW), thousand kernel weight, decortication using the Tangential Abrasive Dehulling Device (TADD) and kernel size. Maize was also characterized for susceptibility to breakage, stress cracking and Near Infrared Transmittance (NIT) Milling Index. Principal component analysis showed that in non-tannin and tannin sorghums TADD hardness and test weight were closely correlated ($p < 0.001$). In maize, TADD hardness was closely correlated with NIT Milling Index and TW. Hence, TADD hardness and NIT Milling Index or TADD hardness and TW would be suitable for maize hardness evaluation. A combination of TADD hardness, TW, TKW and kernel size > 3.35 mm can be used together to select sorghum grain for hardness. It thus appears that TADD hardness is an excellent way of estimating both sorghum and maize hardness that can be applied for routine batch analysis and cultivar evaluation.

INTRODUCTION

In sorghum and maize, grain hardness is the most important parameter for assessing dry milling quality (Munck 1995). In dry milling, a high yield of pure endosperm grits is desirable. Harder grain should give higher milling yield than softer grain (Taylor and Duodu 2009). In turn, grain hardness influences product quality such as porridge stickiness and texture (Bello et al 1995; Rooney et al 1986; Taylor et al 1997). Therefore, simple tests are applied by breeders, millers and traders to estimate hardness and milling properties.

Several tests are used to estimate sorghum and maize grain hardness. These include bulk density tests such as test weight (AACC International 2010), percentage of floaters and density by gas displacement (Paulsen et al 2003). With sorghum, grain decortication using a Tangential Abrasive Dehulling Device (TADD) is commonly used to estimate grain hardness and milling quality (Reichert et al 1986) in terms of time required to remove a certain percentage of the grain (Taylor and Duodu 2009). With maize, endosperm texture can be visually assessed using a light box to determine the relative proportion of corneous to floury endosperm, which is related to grain hardness (Rooney and Miller 1982; Taylor 2003). Alternatively, digital image analysis can used to measure maize kernel translucency (Erasmus and Taylor 2004; Louis-Alexandre et al 1991). Near infrared transmittance and reflectance spectroscopy have also been used to estimate grain hardness (Robutti 1995; Wehling et al 1996) but these methods require calibration against data of standard chemical and physical tests.

Sorghum and maize grain hardness testing methods and their relevance to end use quality are described in detail by Taylor and Duodu (2009). Table I lists simple methods recommended and commonly used for routine analysis in Southern Africa for sorghum (Gomez et al 1997) and maize (SAGL 2005) grain quality evaluation, their advantages, disadvantages and applicability. As can be seen, several grain quality tests are applied for routine grain batch screening and cultivar selection. However, importantly the relationships amongst these test methods are not well understood.

Hence, the objective of the work was to determine the relationships between these simple grain quality tests and their value in commercial sorghum and maize hybrid grain quality selection, with respect to assessing grain hardness.

MATERIALS AND METHODS

Grain Samples

Seventeen sorghum and 35 maize cultivars grown in South Africa representing commercial hybrids were evaluated. They were cultivated during the 2008/2009 growing season. Maize cultivars, all of the white dent type were grown in four localities in the inland summer rainfall region of South Africa (Bethlehem, Klerksdorp, Petit and Potchefstroom). Thirteen red non-tannin and four tannin sorghum hybrids were grown in six localities namely; Klipdrift, Kafferskraal, Goedgedacht, Dover, Platrand, and Parys. To aid interpretation, data from the non-tannin sorghums were evaluated separately those from condensed tannin sorghums.

All samples (5 kg) were thoroughly threshed and cleaned to remove broken and foreign material. The sorghum and maize grain samples were stored at 4°C until analysis.

Quality Tests

Test weight (TW) was determined by the Approved Method 55-10.01 (AACC International 2010) and expressed as kilograms per hectoliter. Sorghum kernel size was done by sieving grain through 4.00 mm, 3.35 mm, 3.15 mm and 2.36 mm opening round hole sieves according to Gomez et al

(1997). Maize kernels were sieved through an 8 mm opening round hole sieve. Maize and sorghum hardness were determined using a Tangential Abrasive Dehulling Device (TADD) (Reichert et al 1986) by decorticating grain for 5 min and measure in terms of the percentage kernel removed. Maize stress cracks (SC) were observed using an illuminated light box and the severity of stress cracking expressed as the stress crack index (SCI) according to Paulsen et al (2003). One thousand kernel (TKW) was determined by weighing 1000 kernels of a representative sample and recording the weight in grams. Breakage susceptibility was determined by running a 100 g sample of whole maize kernels in a Stein Breakage (SB) tester (Fred Stein Laboratories, Atchison, KS) for 4 min and weighing the broken kernels passing through a 6.35 mm round hole opening sieve. Maize Milling Index was measured using near infrared transmittance (NIT), (Infratec 1241, Grain Analyzer, Foss Tecator, Eden Prairie, MN). The NIT calibration was developed against a pilot three break roller milling process. The NIT Milling Index was first developed by roller milling whole grain maize samples through three rollers with gaps widths of 0.30, 0.38, and 0.08 mm. The Milling Index was calculated from relative proportions of meal and bran and used to develop a calibration for a whole grain NIT instrument (Van Loggerenberg and Pretorius 2004). Hardness of whole kernels was analyzed at 860 nm

Statistical analyses

All grain samples were analyzed three times. Data were analyzed by multifactor analysis of variance and means compared by Fisher's Least Significant Differences. Pearson's correlation and principal component analysis (PCA) were performed to determine the relationship among sorghum and maize hardness testing techniques. Calculations were performed using Statgraphics Centurion XV (StatPoint, Herndon, VA).

RESULTS AND DISCUSSION

Table II shows the means and ranges of the non-tannin and condensed tannin sorghum cultivars for TKW, TW, kernel size and TADD decortication. The F-values of these parameters were highly significant ($p < 0.001$) for all sorghums. These data imply that the cultivars varied significantly in the parameters measured. Cultivar and location both had significant effects ($p < 0.001$) and there was cultivar x locality interaction with respect to all the parameters.

The mean TKWs of the non-tannin and condensed tannin sorghums were similar and ranged from 21.7 to 29.0 g and 23.4 to 27.8 g, respectively. Most kernels were distributed in the range >3.35 < 4.00 mm and according to Beta et al (2001) can be classified as of intermediate size. In non-tannin sorghum the coefficient of variation was very low for TW (4.2%), but much higher for TADD decortication (19.9%) and kernel size distribution (4.5% to 115.4%). Similarly, in condensed tannin sorghum, the coefficient of variation was lowest for TW (1.2%) and higher for TADD decortication (18.0%) and kernel size distribution (18.6% to 90.9%). The high %CVs for kernel size and TADD decortication suggest that these parameters could be used to resolve differences in quality between batches of commercial sorghum. The range of TADD kernel removal was from 29.4 to 40.6% and 35.9 to 45.2% for non-tannin and condensed tannin sorghums, respectively. Condensed tannin sorghums are generally softer than non-tannin sorghums (Mwasaru et al 1988), although the TADD data in this study did not indicate substantial differences in hardness between the two.

Table III shows that there were highly significant correlations between TADD hardness (inverse percentage kernel removed) and TW ($r = 0.673$, $p < 0.001$) and TADD hardness and TKW ($r = 0.757$, $p < 0.001$) for the non-tannin sorghums. TADD hardness of non-tannin sorghums was also highly significantly correlated with large kernel size > 4.00 mm ($r = 0.817$, $p < 0.001$), and kernels > 3.35 <

4.00 mm ($r = 0.560$; $p < 0.001$). However, TADD was not correlated with TKW nor with TW for condensed tannin sorghums. This could be partly attributed to the few condensed tannin samples analyzed; hence, limiting variation compared to non-tannin sorghums. The significant ($p < 0.001$) correlations between, TW, TADD, TKW, and kernels retained on 3.35 mm round hole sieve implies that these parameters could be associated with grain hardness in non-tannin sorghum cultivars.

Principal component analysis was performed to further explain the relationships among the parameters. In non-tannin sorghum, the first two components together explained almost 83% of the variability in the data (Fig 1). Principal component (PC) 1 accounted for 56% of the total variation. Large kernel size (> 3.35 mm < 4.00 mm) was associated with TKW, but small kernel size (> 2.36 mm < 3.15 mm) was inversely related to TKW. TADD (% kernel removed) was inversely related to TW. These findings are similar to those of Kirleis and Crosby (1982) who showed that sorghum pearling index, as measured by a Strong-Scott barley pearler, was correlated with kernel density. In condensed tannin sorghums, like non-tannin sorghums, TADD (% kernel removed) was inversely related to TW (PC 2). Thus, for both non-tannin and condensed tannin sorghums, TADD hardness and TW were correlated.

Quality factors of maize had a narrow range for TW but wider for KS, TKW, TADD, and also for NIT Milling Index (Table IV). Locality generally affected the grain quality parameters more than cultivar or cultivar x locality interactions. The TWs of maize cultivars had a narrower range (77.0 to 79.9 kg/hl) than those reported for cultivars grown elsewhere (Duarte et al 2005; Lee et al 2007; Johnson et al 2010). South Africa has selected for hard white maize for many years, hence the closeness of the values. TKW was, however, within the range reported by Duarte et al (2005), Lee et al (2007) and Johnson et al (2010). TADD hardness was remarkably similar for maize (33.8% ± 6.6%) and sorghum (35.1% ± 7.0%). The high %CVs for TKW (12.3%) and TADD decortication (19.5%)

suggest that these parameters could be used to resolve differences in quality between batches of commercial maize.

Stress cracking and breakage susceptibility in maize were characterized by high standard deviations and coefficients of variation (Table IV). Importantly, however, SB, SC and SCI values were very low compared to recommendations by Peplinski et al (1989) of an upper limit of 25% stress cracks and an average of 140 for SCI being preferred (Paulsen et al 2003). The low values indicated that cracking was not a major problem in these maize samples. This was probably because the maize was field dried. Artificial drying greatly increases cracking (Taylor and Duodu 2009). Among yellow dent maize hybrids, Pomeranz et al (1986) found that breakage susceptibility was 0.5 to 43.8% compared to 1.75 to 2.96% obtained in this study for white dent maize hybrids.

Table V shows the relationships among the maize quality parameters. TADD (inverse % kernel removed) was highly significantly correlated with NIT Milling Index ($r = 0.659$, $p < 0.001$), indicating that TADD hardness is related to dry milling grits yield. Despite the narrow range in TW, the parameter was also highly significantly correlated ($p < 0.001$) with NIT Milling Index ($r = 0.540$) and with TADD hardness ($r = 0.636$). High test weights in maize have been associated with a high ratio of hard to soft endosperm, and high milling energies and resistance time to grinding using the Stenvert hardness test (Li et al 1996). These findings are in agreement with those of this present study, as shown by the relationships between TW, NIT Milling Index and TADD hardness.

Kernel size was not correlated with TADD or NIT Milling index. This is in contrast to sorghum where kernels > 3.35 mm were correlated with TADD hardness (Table II). The r values of TKW with TW ($r = 0.415$), NIT milling index ($r = 0.328$) and TADD hardness ($r = 0.435$) were very low and not significant ($p \geq 0.05$), showing that only a small proportion of variation (10 to 19%) was accounted for by these relationships. As would be expected, SC and SCI in maize were highly correlated ($r = 0.873$, $p < 0.001$), although as stated, the level of stress cracking was very low.

With regard to the PCA data for maize, the first two principal components explained almost 65% of the total variation (Fig 3). PC 1 was influenced by TW and TKW and by SB. The second principal component (PC 2) was characterized strongly by TADD and NIT Milling Index, with TADD (% kernel removed) being inversely related to NIT Milling Index. Maize hardness was therefore clearly associated with PC2.

CONCLUSIONS

Not all simple grain quality parameters are related to each other and that a different set of quality tests should be applied for sorghum and for maize grain quality evaluation. TADD, TW, TKW and kernel size > 3.35 mm can be used together to select sorghum grain for hardness. TADD and NIT Milling Index, or TADD and TW are useful for maize. TADD and TW thus seem suitable for evaluating both grain types. These methods to measure grain hardness worked well among the ones tested. However, it is quite possible that others which were not tested would also work. The high CV for TADD for both sorghum and maize indicates that it is useful to distinguish among commercial cultivars specifically for grain hardness.

ACKNOWLEDGEMENTS

Technical support received from Grain Quality Laboratory staff at the Agricultural Research Council-Grain Crops Institute is acknowledged. Financial support from the International Sorghum and Millet Collaborative Research Support Program (INTSORMIL) is greatly appreciated.

LITERATURE CITED

AACC International. 2010. Approved Methods of Analysis, 11th Ed. Method 55-10.01. AACC International: St. Paul, MN.

Bello, A. B., Waniska, R. D., Gomez, M. H., and Rooney, L. W. 1995. Starch solubilization and retrogradation during preparation of *Tô* (a Food Gel) from different sorghum cultivars. Cereal Chem. 72:80-84.

Beta, T., Obilana, A. B., and Corke, H. 2001. Genetic diversity in properties of starch from Zimbabwean sorghum landraces. Cereal Chem. 78:583-589.

Duarte, A. P., Mason, S. C., Jackson, D. S., and Kiehl, D. C. 2005. Grain quality of Brazilian maize genotypes as influenced by nitrogen level. Crop Sci. 45:1958-1964.

Erasmus, C., and Taylor, J. R. N. 2004. Optimising the determination of maize endosperm vitreousness by a rapid non-destructive image analysis technique. J. Sci. Food Agric. 84:920-930.

Gomez, M. I., Obilana, A. B., Martin, D. F., Madzvamuse, M., and Monyo, E. S. 1997. Manual of Procedures for Quality Evaluation of Sorghum and Pearl Millet. ICRISAT: Patancheru, India.

Johnson, W. B., Ratnayake, W. S., Jackson, D. S., Lee, K-M., Herrman, T. J., Bean, S. R., and Mason, S. C. 2010. Factors affecting the alkaline cooking performance of selected corn and sorghum hybrids. Cereal Chem. 87:524–531.

Kirleis, A. W., and Crosby, K. D. 1982. .Sorghum hardness: Comparison of methods for its evaluation. Pages 131-241 in: Proc: Int. Symp. on Sorghum Grain Quality. L. W. Rooney and D. S. Murty, eds. ICRISAT: Patancheru, India.

Lee, K-M, Herrman, T. J., Rooney, L. W., Jackson, D. S., Lingenfelser, J., Rausch, K. D., McKinney, J., Iiams, C., Byrum, L., Hurburgh, C. R., Johnson, L. A., and Fox, S. R. 2007. Corroborative study on maize quality, dry-milling and wet-milling properties of selected maize hybrids. J. Agric. Food Chem. 55:10751-10763.

Li, P. X.-P., Hardacre, A. K., Campanella, H and. Kirkpatrick, K. J. 1996. Determination of endosperm characteristics of 38 corn hybrids using the Stenvert Hardness Test. Cereal Chem. 73:466-471.

Louis-Alexandre, A., Mestres, C., and Faure, J. 1991. Measurement of endosperm vitreousness of corn. A quantitative method and its application to African cultivars. Cereal Chem. 68:614-617.

Mwasaru, M. A., Reichert, R. D., and Mukuru. S. Z. 1988. Factors affecting the abrasive dehulling efficiency of high-tannin sorghum. Cereal Chem. 65:71-174.

Munck, L. 1995. New milling technologies and products: whole plant utilization by milling and separation of the botanical and chemical components. Pages 69-124 in: Sorghum and Millets: Chemistry and Technology. D.A.V. Dendy, ed. AACC International: St Paul, MN.

Paulsen, M. R., Watson, S. A., and Singh, M. 2003. Measurement and maintenance of corn quality. Pages 159–219 in: Corn: Chemistry and Technology, 2nd edn. P. J. White and L. A. Johnson, eds. AACC International: St. Paul, MN.

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., Hall, G. E., Czuchajowska, Z., and Lai, F. S. 1986. Test weight, hardness, and breakage susceptibility of yellow dent corn hybrids. Cereal Chem. 63:349–351.

Reichert, R. D., Tyler, R. T., York, A. E., Schwab, D. J., Tatarynovich, J. E., and Mwasaru, M. A. 1986. Description of a production model of the tangential abrasive dehulling device and its application to breeder's samples. Cereal Chem. 63:201-207.

Robutti, J. L. 1995. Maize kernel hardness estimation in breeding by near-infrared transmission analysis. Cereal Chem. 72:632-636.

Rooney, L. W., and Miller, F. R. 1982. Variations in the structure and kernel characteristics of sorghum. Pages 143-162 in: Proc: Int. Symp. on Sorghum Grain Quality. L. W. Rooney and D. S. Murty, eds. ICRISAT: Patancheru, India.

Rooney, L. W., Kirleis, A. W., and Murty, D. S. 1986. Traditional foods from sorghum: Their production evaluation and nutritional value. Pages 317-353 in: Advances in Cereal Science and Technology. Vol. VIII. Y. Pomeranz, ed. AACC International: St. Paul, MN.

Southern African Grain Laboratory (SAGL). 2005. Maize Laboratory Training Manual. SAGL:Pretoria, South Africa.

Taylor, J. R. N. 2003. Overview: Importance of Sorghum in Africa. Paper 1 in: AFRIPRO, Workshop on the Proteins of Sorghum and Millets: Enhancing Nutritional and Functional Properties for Africa.P. S. Belton and J. R. N. Taylor, eds. http://www.afripro.org.uk/papers/Paper01Taylor.pdf (accessed on 10 October 2010).

Taylor, J. R. N., and Duodu, K. G. 2009. Applications for non-wheat testing methods. Pages

197-234 in: The ICC Handbook of Cereals, Flour, Dough and Product Testing. Methods and Applications. S. P. Cauvain and L. S. Young, eds. DEStech Publications, Lancaster, PA.

Taylor, J. R. N., Dewar, J., Taylor, J., and Von Ascheraden, R. F. 1997. Factors affecting the porridge-making quality of South African sorghums. J. Sci. Food Agric. 73:464-470.

Van Loggerenberg, D., and Pretorius, A. J. 2004. Determining the milling index of maize with a NIT calibration. Proc. S. Afr. Soc. Crop Prod. Cong. Bloemfontein, South Africa.

Wehling, R. L., Jackson, D. S., and Hamaker, B. R. 1996. Prediction of corn dry milling quality by near-infrared spectroscopy. Cereal Chem. 73:543-546.

TABLE I

Simple Methods used in Southern Africa for Sorghum and Maize Grain Quality Evaluation, their Advantages, Disadvantages and Applicability

Method and Apparatus	Parameter/quality indicator measured	Advantages	Disadvantages	Applicability
Test weight Test weight per bushel or kg/hl apparatus	Grain density	Inexpensive device, low maintenance cost Rapid, high repeatability and reproducibility Non-destructive method	Affected by grain packing in measuring apparatus, moisture content, kernel shape, broken kernels and foreign material Not suitable for early generation breeding	Applicable to breeding programs and cultivar evaluation with limited grain sample size. Rapid test on dockage for commercial large and small- scale milling plants and grading for grain marketing
Thousand kernel weight Seed counter and balance	Grain size and Grain density	High repeatability and reproducibility, non-destructive indirect measure of grain density	Time consuming if done manually (without a seed counter)	Suitable for breeding programs with limited grain sample size. Also applicable in commercial grain quality control and processing, both large and small-scale
Abrasive Decortication Tangential Abrasive Dehulling Device (TADD)	Ease of grain to be abraded- indirect measure of grain hardness and milling quality	TADD is robust and can be applied to both maize and sorghum High repeatability and reproducibility Low maintenance cost Equipment can be manufactured locally	The abrasive disk may be worn out with the time and vary milling yields although this can be monitored with the use of a standard sample of known yield.	Potential use at commercial level (both small and large scale) The multi-cup sample holder allows several samples to be decorticated simultaneously within a short time (5 to 10 min)
Stress cracks Light box	Proportion of grain with cracks and number of cracks	Apparatus cheap to set up Stress cracks may be quantified using the Stress Crack Index	Stress crack counting tedious and time consuming and to a degree subjective Unsuitable for sorghum as it is opaque and does not transmit light like maize	Time consuming for routine analysis, but suitable for small sample size
Stein Breakage Susceptibility Stein Breakage Tester	Susceptibility of grain to break under stress	Allows quantification of the potential of grain to break. Rapid analysis (4 min)	Apparatus is no longer manufactured, although other mills may be used	Suitable for commercial grain evaluation. Destructive, could have limited use in breeding programs where grain sample size is limiting
Milling Index Near Infrared Transmittance (NIT) spectrometry	Grain milling quality	Automated and rapid analysis once a calibration is developed Calibration can be used by other users. None destructive method.	Requires calibration against physical or chemical data which, could be time consuming and costly Very sensitive to sample preparation affecting precision and accuracy High initial cost to purchase the instrument and operating software Regular software and service upgrade required. Requires a relatively large grain sample size (approx 500 g)- limited use in breeding programs where grain sample	Rapid for online processing at commercial milling plants and routine analysis in breeding programs and cultivar evaluation Skilled technical maintenance required Use could be limited to well established institutions; not economically appropriate for small-scale grain quality control and processing

			size is limiting	
Kernel size Set of sieves and sieve shaker	Kernel size	Analysis is relatively cheap. Non-destructive. Direct measure of kernel size. Does not require a large grain sample size	Can be time-consuming especially if batches are very heterogeneous in terms of kernel size.	Due to lengthy analysis time, it is not applicable in commercial grain quality analysis. Applicable in research laboratories.

TABLE II

Thousand Kernel Weight, Test Weight, Kernel Size Distribution and Kernel Removal by TADD Decortication of Non-Tannin and Condensed Tannin Sorghum Cultivars Grown in Six Localities

	TKW	TW	>4.00	>3.35<4.00	>3.15<3.35	>2.36<3.15	TADD
Non-Tannin Sorghum[a]							
Mean	25.7 (1.9)	75.7 (3.2)	1.0 (1.2)	42.1 (16.3)	25.2 (7.2)	26.9 (1.2)	35.1 (7.0)
Range	21.7-29.0	74.0-77.1	0.4-0.9	23.4-59.5	18.0-31.0	15.0-47.4	29.4-40.6
%CV	7.4	4.2	115.4	38.7	28.6	4.5	19.9
F value (C)	14.2***	18.7***	48.4***	250.8***	121.6***	421.4***	41.1***
F value (L)	17.0***	16.8***	84.2***	1064.2***	634.2***	1661.6***	121.4***
F value (C x L)	2.5***	5.6***	13.1***	59.7***	48.8***	81.0***	10.0***
Condensed Tannin Sorghum[b]							
Mean	25.5 (3.3)	74.0 (0.9)	1.1 (1.0)	42.8 (12.1)	25.8 (4.8)	26.1 (9.1)	40.5 (7.3)
Range	23.4-27.8	71.9-74.2	0.4-1.7	29.2-56.3	20.4-31.9	17.6-34.8	35.9-45.2
%CV	12.9	1.2	90.9	28.3	18.6	34.9	18.0
F value (C)	13.2***	94.0***	63.5***	1648.6***	237.1***	342.7***	37.9***
F value (L)	8.6***	71.0***	39.3***	491.8***	35.4***	194.2***	59.2***
F value (C x L)	2.4***	11.3***	22.4***	94.4***	18.6***	21.6***	13.6***
Overall for Non-Tannin and Condensed Tannin Sorghums							
Mean	25.6 (2.7)	74.7 (1.5)	1.1 (0.9)	42.3 (14.1)	25.3 (6.5)	26.7 (11.5)	36.4 (6.0)
Range	21.7-29.0	71.9-77.1	0.4-1.7	23.4-59.5	18.0-31.9	15.0-47.7	29.4-45.2
%CV	10.5	0.7	8.6	33.3	25.7	43.1	16.5
F value (C)	18.7***	33.8***	48.1***	388.2***	147.0***	372.0***	55.1***
F value (L)	32.6***	21.7***	115.7***	1400.0***	608.8***	1642.1***	161.6***
F value (C x L)	3.7***	6.3***	14.5***	65.5***	38.5***	63.8***	11.9***

Data in parentheses are standard deviations

Significance at $p < 0.001$ denoted by ***,.

TW, test weight (kg/hl); TKW, thousand kernel weight (g); TADD (% kernel removed); 4.00 mm, 3.35 mm, 3.15 mm and 2.36 mm; percentage kernels retained on the respective sieve sizes; C, cultivar; L, locality; C x L, cultivar x locality interactions

[a] Data of 13 cultivars cultivated in 6 locations (n=78)

[b] Data of 4 cultivars cultivated in 6 locations (n=24)

TABLE III

Pearson Correlation Coefficients between Test Weight, Thousand Kernel Weight, Kernel Size Distribution and TADD Kernel Removal of Non-Tannin and Condensed Sorghum Cultivars Grown in Six Localities

	TW	TKW	>4.00	>3.35<4.00	>3.15<3.35	>2.36<3.15
			Non-Tannin Sorghum			
TKW	0.242ns					
>4.00	0.134ns	0.317ns				
>3.35<4.00	0.191ns	0.567***	0.602***			
>3.15<3.35	0.004 ns	-0.213ns	-0.591***	-0.649***		
>2.36<3.15	-0.195ns	-0.586***	-0.485***	-0.929***	0.497ns	
TADD	-0.673***	-0.757***	-0.817***	-0.560***	-0.197 ns	0.101ns
			Condensed Tannin Sorghum			
TKW	0.122 ns					
> 4.00	0.101 ns	0.560***				
>3.35<4.00	0.212 ns	0.677***	0.327ns			
>3.15<3.35	-0.124 ns	-0.561***	-0.093ns	-0.812***		
>2.36<3.15	-0.160 ns	-0.663***	-0.028ns	-0.926***	0.753***	
TADD	-0.327ns	0.212 ns	-0.064ns	-0.354ns	-0.098ns	-0.423ns

Significance at $p < 0.001$ denoted by ***, ns- not significant ($p > 0.05$).

TW, Test weight (kg/hl); TKW, thousand kernel weight; TADD (% kernel removed); 4.00 mm, 3.35 mm, 3.15 mm and 2.36 mm; percentage kernels retained on the respective sieve opening sizes.

TABLE IV

Test Weight, Breakage Susceptibility, Kernel Size, Stress Cracking, Thousand Kernel Weight, TADD Kernel Removal and NIT Milling Index of Maize Cultivars[a] Grown in Four Localities

Cultivar	TKW	TW	KS	SB	SC	SCI	TADD	NIT
Mean	381 (47)	78.3 (2.8)	76.8 (7.2)	2.15 (1.33)	3.23 (3.98)	8.10 (11.50)	33.8 (6.6)	86.2 (12.4)
Range	335-412	77.0-79.9	61.9-81.6	1.75-2.96	1.00-4.17	2.00-17.58	30.0-39.1	69.0-94.8
%CV	12.3	3.6	9.4	61.9	123.2	142.0	19.5	14.4
F value (C)	2.5***	1.5*	4.7***	1.1 ns	1.3 ns	1.4 ns	4.5***	11.1***
F value (L)	53.0***	142.7***	3.0*	43.4***	47.3***	39.6***	209.1***	281.6***
F value (C x L)	0.8 ns	0.8 ns	1.3*	1.0 ns	0.9 ns	0.8 ns	1.5**	3.8***

Data in parentheses are standard deviations

Significance at $p < 0.05$, 0.01 and 0.001 denoted by *, **, ***, respectively, ns- not significant ($p > 0.05$).

TW, test weight(kg/hl); SB, % breakage susceptibility by Stein Breakage Tester; SC, % stress cracks; SCI; stress crack index; TKW; Thousand kernel weight(g); TADD (% kernel removed); KS; % kernel size ≥ 8 mm; NIT, NIT milling index; C, cultivar; L, locality; C x L, cultivar x locality interactions

[a]Data of 35 maize cultivars cultivated in 4 locations (n=140)

TABLE V

Pearson Correlation Coefficients between Test Weight, Breakage Susceptibility, Kernel Size, Stress Cracking, Thousand Kernel Weight, TADD Kernel Removal and NIT Milling Index of Maize Cultivars Grown in Four Localities

	TW	SB	SC	SCI	TKW	TADD	KS
SB	0.085ns						
SC	0.126ns	0.285ns					
SCI	0.128ns	0.265ns	0.873***				
TKW	0.415ns	0.041ns	0.180ns	0.199ns			
TADD	-0.636***	-0.155ns	-0.194ns	-0.172ns	-0.435ns		
KS	0.108ns	0.013ns	0.051ns	0.030ns	0.100ns	-0.065ns	
NIT	0.540***	0.112ns	0.151ns	0.145ns	0.328ns	-0.659***	0.067ns

Significance at $p < 0.001$ denoted by ***, ns- not significant ($p > 0.05$).

TW, Test weight(kg/hl); SB, % breakage susceptibility by Stein Breakage Tester; SC, % stress cracks; SCI; Stress crack index; TKW; Thousand kernel weight(g); TADD (% kernel removed); KS; % kernel size ≥ 8 mm; NIT, NIT milling index.

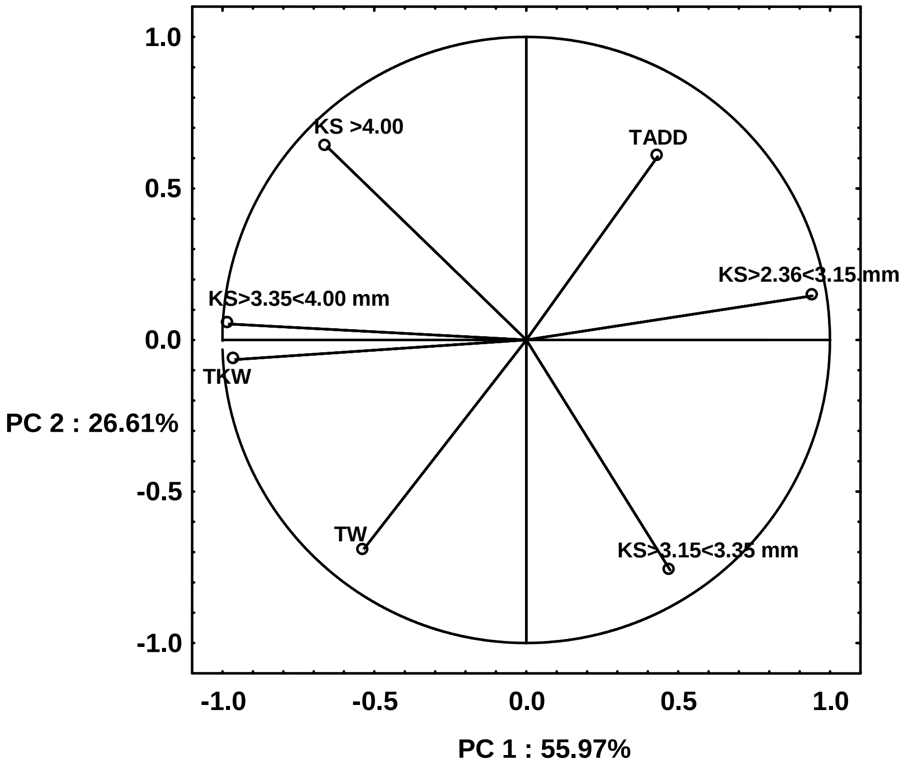

Fig. 1. Factor coordinates of the first two principal components (PC) for non-tannin sorghums with respect to test weight (TW), thousand kernel weight (TKW), kernel size (KS) fractions and Tangential Abrasive Dehulling Device (TADD) (% kernel removed) properties

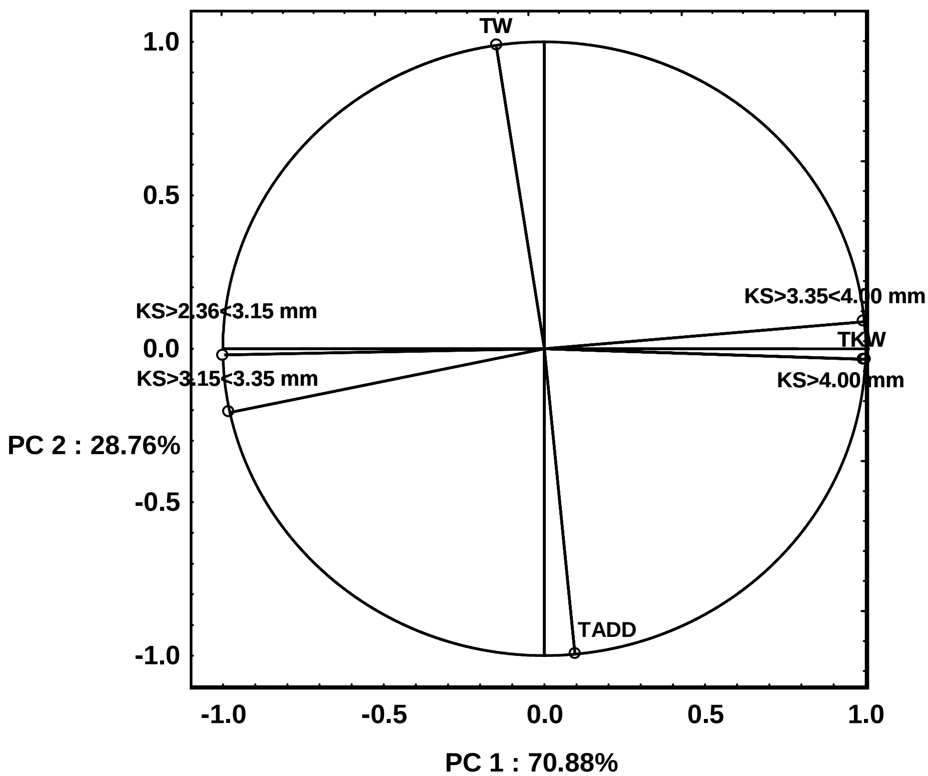

Fig. 2. Factor coordinates of the first two principal components (PC) for condensed tannin sorghums with respect to test weight (TW), thousand kernel weight (TKW), kernel size (KS) fractions and Tangential Abrasive Dehulling Device (TADD) (% kernel removed) properties

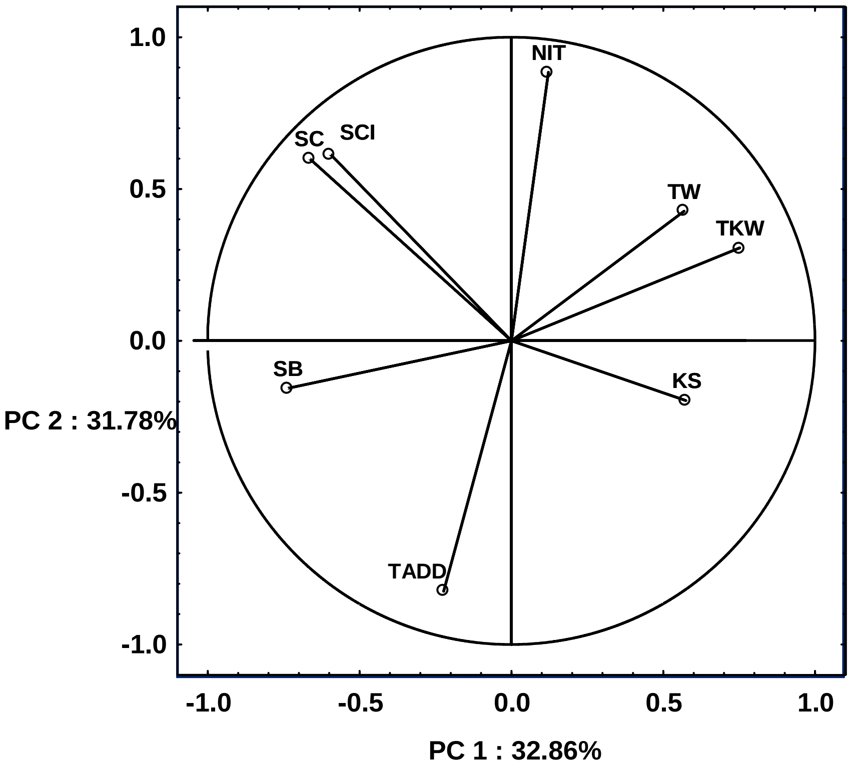

Fig. 3. Factor coordinates of the first two principal components (PC) for maize with respect to test weight (TW), Stein Breakage (SB), stress cracks (SC), stress cracking index (SCI) thousand kernel weight (TKW), kernel size (KS), Tangential Abrasive Dehulling Device (TADD) (% kernel removed) and NIT Milling Index properties