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Physical properties of kernels from modern maize hybrids used in Croatia

Kristina KLJAK (✉), Klara NOVAKOVIĆ, Dora ZURAK, Marieta JAREŠ, Santina PAMIĆ, Marija DUVNJAK, Darko GRBEŠA

University of Zagreb, Faculty of Agriculture, Department of Animal Nutrition, Svetošimunska 25, 10000 Zagreb, Croatia

✉ Corresponding author: kkljak@agr.hr

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ABSTRACT

The physical properties of maize are a result of kernel structure, they indicate chemical properties of the kernel, and hence, its nutritive value. This research aimed to explore the physical traits of kernels of 80 commercial maize hybrids from nine seed companies. The grain from investigated hybrids was produced during the same season on the same field under the same agricultural conditions. Moisture content, bulk and real density, Stenvert hardness (time to grind 17mL of grits, height of freshly ground grain, and coarse-to-fine particles ratio, C/F), flotation index, breakage susceptibility, kernel dimensions, and sphericity were determined in maize samples. Test weight was in a range from 70.2 to 82.1 kg/hL. Density ranged from 1.159 to 1.301 kg/L and similarly as test weight increased with increasing hardness (C/F; r=0.52 and 0.68, respectively; P<0.001); a trait that is related to breakage and insect resistance, and to decreased starch digestibility. Flotation index was from 8 to 100%, and its value decreased with increasing hardness (r=-0.65; P<0.001). A wide range of values in physical traits of investigated hybrids implies different behavior of grain during postharvest handling and processing and thus variable nutritive value.

Keywords: maize grain, hybrid, density, hardness, bulk density, sphericity

SAŽETAK

Fizikalna svojstva kukuruza posljedica su strukture zrna te upućuju na kemijska svojstva zrna, a time i na njihovu hranidbenu vrijednost. Cilj ovog istraživanja je bio ispitati fizikalna svojstva zrna 80 komercijalnih hibrida kukuruza. Zrno istraživanih hibrida kukuruza proizvedeno je tijekom iste vegetacijske sezone na istom polju i u uvjetima iste agrotehnike. U uzorcima je određen sadržaj vlage, hektolitarska masa, gustoća, tvrdoća prema Stenvertu (vrijeme mljevenja 17 mL meljave, visina stupca meljave te omjer sitnih i krupnih čestica, K/S), flotacijski indeks, lomljivost, dimenzije zrna i sferičnost. Hektolitarska masa zrna kretala se od 70,2 do 82,1 kg/hL. Uz raspon vrijednosti od 1,159 do 1,301 g/mL, gustoća, kao i hektolitarska masa, je rasla s porastom tvrdoće zrna (K/S parametar; r=0,52 i 0,68; P<0,001), svojstvom koje je povezano s otpornošću zrna na lom i insekte, ali i sporijom probavljivošću škroba. Flotacijski indeks je bio između 8 i 100%, a njegova vrijednost je opadala s porastom hektolitarske mase (r=-0,65; P<0,001). Širok raspon vrijednosti fizikalnih svojstava zrna istraživanih hibrida upućuje na različito ponašanje tijekom rukovanja, ali i na različitu hranidbenu vrijednost zrna.

Ključne riječi: zrno kukuruza, hibrid, gustoća, tvrdoća, hektolitarska masa, sferičnost

INTRODUCTION

Maize (*Zea mays* L.) grain is one of the most important and cultivated crops in the world, and its yearly production is about 1,135 million metric tons (NCGA, 2020). Different maize hybrids vary in texture and hardness of kernel and, consequently, in its processing and use in human and animal nutrition. The majority (61.6%) of worldwide produced maize is yellow and used as energetic feed whereas hybrids considerably vary in physical properties (Rodehutscord et al., 2016), chemical composition (Bullock at al., 1989; Blandino at al., 2010), digestibility (Giuberti et al., 2013; Seifried et al., 2016), and energy (15.7 – 16.8 MJ/kg) content for pigs (Opapeju et al., 2007) and poultry (Zuber and Rodehutscord, 2017). Even maize hybrids with similar nutrient profiles differ in their effect on animal performances (Colins at al., 2001; Gehring at al., 2012).

From a nutritional point of view, it is very interesting to use physical properties of maize kernels as a rough and quick predictor of feeding value due to their relationship with chemical composition, extent and rate of digestibility (Philippeau et al.,1999; Grbeša, 2016) and animal production performance, specifically, feed efficiency in broilers (Colins et al., 2001), egg and pig production (Moore et al., 2008a, 2008b) and beef fattening (Jaeger et al., 2006; Harlesson et al., 2019). Even selection to maize yield worldwide is associated with a change in the physical properties of kernels (Vyn and Tollenaar, 1998; Abdala et al., 2018).

The main component of maize is starch, and kernel structure and hardness influence the extent and rate of glucose release, which ultimately affects the efficiency of energy utilization. Studies have shown the importance of hardness; softer maize grain with a higher content of floury endosperm have greater starch digestibility in ruminants (Philippeau et al., 2000; Correa et al., 2002) and pigs (Giuberti et al., 2013; Odjo et al., 2017). However, it should be noted that higher digestibility of starch does not necessarily imply better utilization – harder hybrids with a higher proportion of vitreous endosperm have a slower rate of glucose release and better utilization of energy in poultry (Benedetti et al., 2011; Zhao et al., 2016; Singh and Ravindran, 2019) and pigs (Doti et al., 2014).

Numerous tests are in use to determine maize kernel's physical quality grade; among the main ones are moisture, test weight, 1,000 kernel weight, density, Stenvert hardness, flotation index, kernel sphericity, breakage susceptibility and heat damage (Henry and Kettlewell, 1996). Physical tests vary, but they could give complementary information about maize nutritive value. The most widespread is test weight, a general indicator of overall quality, and a rough measure of endosperm hardness, kernel type and nutritive value of maize (Čuklić et al., 2015; US Grains Council, 2019). The initial test weight depends on genetic differences in the structure and chemistry of the kernels. However, the overall final value is affected by moisture content, methods of drying, physical damage, presence of foreign materials, stress during the growing season, and microbiological damage (Henry and Kettlewell, 1996). Test weight is commonly determined after harvest where higher values are associated with lower contents of ash, crude fiber, and crude protein and higher endosperm vitreousness, while low values indicate lower contents of starch and oil and lower vitreousness (Lee et al., 2006; Grbeša, 2016; Navarro et al., 2018). Flint and semiflint genotypes have higher test weight (79.6 and 77.8 kg/hL, respectively) than dent (Abdala et al., 2018). Generally among diets, varying test weight is associated with variable dry matter and energy digestibility and both digestible and metabolisable energy content (Navarro et al., 2018). In ruminants, maize test weight negatively correlated with degradability of crude protein and starch in the rumen (Seifried et al., 2016).

The bulk of maize grain contains on average 42.3% of void space between kernels, and thus, the 1,000 kernel weight is a more precise measurement than test weight (Thompson and Isaacs, 1967). Hegyi et al. (2007) showed that 1,000 kernel weight of 100 hybrids highly correlates with starch content (r=0.91) and moderately with yield (r=0.72), and thus is an excellent indicator of both traits. Furthermore, hybrids differ in 1,000 kernel weight which positively correlates with hardness, feed conversion and dry matter digestibility (Jaeger et al., 2006; Harlesson et al., 2019). Since it is based on grain weight, the same relationship can be attributed to the density, and the grains of lower density are considered softer (Fox and Manley, 2009). The specific density, or in the case of cereals, the flotation index is determined by the number of kernels floating in the solution of sodium nitrate of a specific concentration.

In comparison to grain with a high percentage of floaters, grain with a low percentage have a higher density and usually harder endosperm more resistant to damage (Radosavljević et al., 2000). The floating test in a sodium nitrate solution has shown to be an indicator of hardness since hard grains (flint) are denser and float to a lesser degree than those with lower density (floury or dent). However, similarly to test weight, floating grain quantification does not measure the proportion of floury and vitreous endosperm.

Grain hardness is an intrinsic property of the maize, related to its nutritive value. Common hardness markers are test weight and density, but the most used is Stenvert test (Pomeranz et al., 1985; Li et al., 1996; Blandino et al., 2010) measuring the time needed to grind the sample and the height of the grits in the collection tube. The ratio of coarse to fine particles is also measured. Hybrids with a higher proportion of vitreous endosperm give coarser grits that results in their lower height in the collection tube and higher coarse-to-fine particles ratio than in hybrids with a higher proportion of floury endosperm. Hybrids with kernels of higher hardness have higher resistance and nutritional value due to the higher proportion of vitreous endosperm. The use of hybrids of higher hardness results in higher finishing weights of pigs (Moore et al., 2008a) and higher egg production in laying hens which is accompanied with better feed-to-gain ratio (Moore et al., 2008b).

Breakage sensitivity is defined as the potential for fragmentation or cracking/breaking of kernel when the grain is subjected to impact force during handling or transport (AACC, 1995). The lowest breakage is when the grain is harvested at 22% of moisture while drying increases its breakage susceptibility resulting in higher susceptibility of harder compared to softer kernels (Pomeranz et al., 1986; Kirleis and Stroshine, 1990). Breakage decreases maize nutritional value due to the nutrient loss occurring; broken grains are more susceptible to mold infection during storage (Grbeša, 2016).

The relationship of physical properties is a result of the grain structure, and this has been previously investigated (Gaytán-Martínez et al., 2006; Lee et al., 2007; Blandino et al., 2010) but mainly in relation to grinding performance or hardness and during maize use in human and not animal nutrition. Furthermore, these studies do not cover a large number of hybrids that are currently commercially available on the market. Therefore, this study aimed to determine the physical properties of 80 common maize hybrids, recently present on the market and produced under the same conditions, and to examine the relationship between them.

MATERIALS AND METHODS

In total, 80 maize hybrids from different seed companies were used in the study (Table 1). All hybrids were grown during the same year in the same field in Eastern Croatia, under the same intensive agricultural conditions. Each hybrid was planted in 8 rows on the test lot 100 m long while sowing density was according to the recommendations of the seed companies (55,000 – 75,000 plants/ha). The crops were fertilized with nitrogen and phosphorous, and weeds, diseases, and insects were appropriately controlled throughout the growing season using commercially recommended products. Five locations along test lots were selected to collect hybrid samples; 5 cobs from each of the location were harvested after hybrid reached physiological maturity. The grain from all 5 locations for each hybrid was mixed, and a representative sample was taken by quartering. Grain moisture at harvest of tested hybrids was between 16.7 and %. After delivery to the laboratory, all hybrids were dried at 60 °C and stored at +4 °C until analyses.

Table 1. List of tested maize hybrids

Hybrid	Hybrid	Hybrid	Hybrid
LG Agrister	RWA Da Scipio	PIO Os 499	Bc Institut Bc 424
LG 35.40	RWA Futurixx	PIO Os 378	Bc Institut Bc 462
LG 30.325	RWA Labeli	PIO Ossk 396	Bc Institut Bc 532
LG 30.491	Syngenta NK Columbia	PIO Ossk 403	Bc Institut Bc 572
LG 33.50	Syngenta NK Helico	PIO Ossk 515	Bc Institut Bc 574
LG 362/92	Syngenta NK Lucius	MAS 47.P	Bc Institut Bc 582
LG 34.75	Syngenta NK Octet	MAS 51.G	Bc Institut Bc 616
KWS Amandha	Syngenta NK Pako	MAS 56.A	Bc Institut Bc 678
KWS Kerberos	Syngenta NK Timic	MAS 58.M	Bc Institut Klipan
KWS Kinemas	Syngenta SY Affyinity	MAS 59.P	Bc Institut Pajdaš
KWS Kitty	Syngenta SY Ondina	NS seme NS 3014	Pioneer P0216
KWS Klimt	Sangenta SY Ulises	NS seme NS 4015	Pioneer P0412
KWS Korimbos	DKC 5222	NS seme NS 5043	Pioneer P9494
KWS Krebs	DKC 5276	NS seme NS 6030	Pioneer P9915
KWS 3381	DKC 5401	NS seme NS 6102	Pioneer PR34N43
RWA Axxo	DKC 5276	NS seme NS 6010	Pioneer PR35F38
RWA Cadixxio	DKC 5707	Bc Institut Bc 306	Pioneer PR36K67
RWA Gasti	DKC 4795	Bc Institut Bc 344	Pioneer PR36V74
RWA Sherley	PIO[1] Drava 404	Bc Institut Bc 354	Pioneer PR37N01
RWA Ulyxxe	PIO Os 430	Bc Institut Bc 406	Pioneer PR37Y12

[1] PIO – Agricultural Institute Osijek

Physical methods

Grain density was determined using a pycnometer with ethanol, and the test weight was calculated by dividing 1,000 kernel weight by 1,000 kernel volume. The flotation index was determined by the number of floating grains in 100 mL of sodium nitrate solution of a relative density 1.26 according to the method described by Fox and Manley (2009). The grain hardness using Stenvert test was determined with the Stenvert-Pomeranz method described by Pomeranz et al. (1985); 20 g of sample was ground using a hammer mill (Polymix PX-MFC 90 D, Kinematica, Italy) equipped with a 2 mm sieve at 3,600 rpm, and time required to grind 17 mL of grits, the height of the grits in grinding column and the ratio of coarse (>0.8 mm) to fine particles (<0.5 mm; C/F) were measured. For the determination of C/F, all the mass obtained by grinding 20 g of the sample was sieved through 0.8- and 0.5-mm sieves on an AS 200 basic sieve shaker (Retsch, Germany). Breakage susceptibility was determined using the HT-I drop tester constructed according to the scheme described by Kim et al. (2002). Each of the 20 grains was individually broken by an aluminium bar from a height of 15 cm with an impact energy of 0.3 N. All mass was collected and sieved through a 4.75 mm sieve, and the breakage susceptibility was calculated as the fraction of grains passed through a sieve. Grain dimensions were determined by a digital scaling scale, and sphericity was calculated based on height, width, and thickness (Matin et al., 2007).

Since physical properties of cereal grain depend on the moisture content of the sample, moisture of dried and stored maize samples was determined for all the hybrids tested immediately before analyses. The samples were dried in the oven at 103±2 °C until constant weight (HRN ISO 6496: 2001). All results of the physical properties were then expressed at the moisture content of 12% and calculated according to the equations given by Dorsey-Redding et al. (1990).

Statistical analysis

All physical analyses were performed in duplicate and repeated in case of deviations; results are showed as an average value of all measurements for each hybrid. The relationship between determined physical properties of the tested hybrids was examined using correlations. The PROC CORR procedure of the SAS 9.4 statistical package (SAS Institute Inc., Cary, NC) was used. Correlations were statistically significant if P>0.05.

RESULTS AND DISCUSSION

The determined traits are presented at 12% moisture as it is a requirement for feed storage for longer than one year (MWPS-13, 1988). Drying reduces kernels moisture content and void space and consequently increases test weight and density (Thompson and Isaacs, 1967). Although 80 ordinary commercial hybrids compared in the present study are typically cultivated in Croatia, they widely differed in all measured kernel physical traits (Tables 2, 3 and 4).

The average test weight was 74.67±2.08 kg/hL and varied considerably between 70.19 and 82.05 kg/hL (Table 2). These values were similar to values of 72 US maize hybrids (in average 76±2 kg/hL) from multiple locations (Harlesson et al., 2019) and 32 hybrids (76.7±2.44 kg/hL) from one breeding company across five years (Grbeša, 2016). Test weights of majority hybrids tested in the present study were well above the minimum for US Grade No 1 (72.08 kg/hL; Paulsen et al., 2003).

The average 1,000 kernel weight was 332 g (Table 2), and the obtained range (270 to 397 g) was similar to the values obtained in other studies (Peplinski et al., 1992; Blandino et al., 2010; Milašinović Šeremešić et al., 2019). Most of the hybrids in this study had a 1,000 kernel weight between 300 and 350 g, while the weight of less than 300 g had 9% and higher than 350 g 21% of the tested hybrids. Peplinski et al. (1992) have shown that grains with a higher 1,000 kernel weight are also of greater hardness, implying higher vitreousness. Moore et al. (2008a and 2008b) found a strong association between 1,000 kernel weight and better feed utilization in broilers and egg production and in growing but not an early phase of pig growth. However, their nutritional potential can be implied not only from the 1,000 kernel weight, but also from the volumes occupied by these grains, and the test weight is, therefore, a better indicator. It is not always the case that hybrids of high 1,000 kernel weight have high test weight or vice versa; for example, hybrid Bc 572 had one of the lowest 1,000 kernel weight but high test weight of 75.72 kg/hL.

Kernel density is a more accurate volumetric measurement of hardness and feed value than the test weight since it does not take into account the space between the kernels (Henry and Kettlewell, 1996).

Table 2. The 1,000 kernel weight and volume, and bulk and true density of kernels from tested hybrids

Physical trait	Average	Standard deviation	Minimum	Maximum
Test weight, kg/hL	74.67	2.08	70.19	82.05
1,000 kernel weight, g	332	25.19	270	397
1,000 kernel volume, g	445	37.23	345	538
Density, g/mL	1.223	0.03	1.159	1.301

Table 3. Flotation index and Stenvert hardness[1] of kernels from tested hybrids

Physical trait	Average	Standard deviation	Minimum	Maximum
Flotation index, %	82.64	19.22	8	100
Stenvert hardness				
Time, s	3.46	0.51	2.70	5.94
Height, mm	95.38	6.35	77.90	109.12
C/F	0.994	0.102	0.556	1.754

[1] Stenvert hardness variables: time required to grind 17 mL of grits – time, column height of freshly ground 20 g of maize kernels (height) and the ratio of coarse (>0.8 mm) and fine (<0.5 mm; C/F) particles in freshly ground 20 g of maize kernels

Table 4. Breakage susceptibility, dimensions and sphericity of kernels from tested hybrids

Physical trait	Average	Standard deviation	Minimum	Maximum
Breakage susceptibility, %	24.67	10.39	7.10	64.88
Kernel height, mm	12.34	0.62	10.56	13.84
Kernel width, mm	8.30	0.41	7.23	9.38
Kernel thickness, mm	4.97	0.28	3.51	5.13
Sphericity	0.64	0.03	0.56	0.77

The hybrids tested in this study had a range of density from 1.159 to 1.301 g/mL (Table 2). This range is identical to the density of USA maize (1.15-1.35 g/mL; US Grains Council, 2019) and similar to the values reported by Fox et al. (1992; 1.20-1.30 g/mL) and Kljak et al. (2011; 1.051-1.278 g/mL). Among investigated hybrids, only 9% had density values above 1.26-1.28 g/mL and can be generally considered as hard (Henry and Kettlewell, 1996). Fox and Manley (2009) established even stricter criteria that hard grains have density above 1.40 g/mL. On the other hand, Gaytán-Martínez et al. (2006) have shown that the grains with the densely packed structure of more vitreous hybrids have higher density. Thus, hybrids of higher density will have better nutritional value in poultry and pig feeding (Moore et al., 2008a; Benedetti et al., 2011; Zhao et al., 2016) and lower ruminal starch (Lopes et al., 2009) and protein degradability (Seifried et al., 2016) in ruminants.

The flotation index of 80 hybrids tested in the present study was 82.64% on average, but it varied in a vast range from 8 to 100% (Table 3). The obtained range agrees with the values reported by Peplinski et al. (1992; 11-64%) and Radosavljević et al. (2000; 1-71%). The semident kernels have a flotation index below 25% (Brown and Darrah, 1985) while flint kernels only 4% (Abdala at al., 2018). The majority of hybrids tested in the present study had flotation index over 56%, and according to Weber et al. (2014), they are members of dent-type hybrids. The higher proportion of floating kernels implies lower hardness, vitreousness and breakage susceptibility (Peplinski et al. 1992; Gaytán-Martínez et al. 2006; Blandino et al. 2010) and thus less nutritional value for poultry and pigs.

The grain hardness of tested hybrids was estimated through three parameters of the Stenvert test based on the milling of 20 g of maize sample, and the average, minimum and maximum values of these variables for 80 hybrids are shown in Table 3. In average, it took 3.46 s to grind 17 mL of grits, and an average height of ground sample was 95.38 mm. However, according to Fox and Manley (2009), these results gave a contradictory estimation of hardness among tested samples – based on grinding time, hybrids were soft (time <10 s) while based on the height of grits, they were hard (height <200 mm). The inconsistency of the milling conditions or mill used for grinding caused the observed difference between studies. In comparison to 3600 rpm in this study, Blandino et al. (2010) ground the grains at 2500 rpm, and it took from 5.5 to 10.02 s to ground 17 mL of grits. The coarse-to-fine particles ratio in freshly ground samples ranged from 0.556 to 1.754, and this was the most variable of all Stenvert hardness parameters in the present study. Hybrids tested in studies by Pomeranz et al. (1985; 1.19-1.83) and Blandino et al. (2010; 0.5-1.4) obtained similar values. All three Stenvert parameters gave a similar distribution of hardness among tested hybrids, which is in accordance with the correlations between them: the coarse-to-fine particles ratio and the grinding time – r=0.78 (P<0.001), coarse-to-fine particles ratio and column height – r=-0.78 (P<0.001), and grinding time and column height – r=-0.77 (P<0.001).

Jaeger et al. (2006) and Harlesson at al. (2019) have shown that fattening cattle have better feed-to-gain ratios when fed hybrids with softer grains – those with a higher column height of freshly ground sample and a lower coarse-to-fine particles ratio. On the other hand, it has already been mentioned that hybrids of higher vitreousness are better utilized by poultry and pigs (Moore et al. 2008a, 2008b). Grain hardness is also associated with resistance to insects and molds; for example, de Oliveira et al. (2009) showed that harder grains would be less infected with molds of the genus *Fusarium* sp, while Blandino and Reyneri (2008) showed that grains with harder endosperm were 50% less contaminated with fumonisin B1 than softer grains.

The breakage susceptibility was determined using the drop tester with an impact energy of 0.3 J, and average, minimum and maximum values of 80 maize hybrids are shown in Table 4. Tested hybrids varied from 7.10% to 64.88%, which indicates substantial genotype effect since moisture of dried grain was similar among hybrids (9.72 – 10.81%). Results by Stroshine et al. (1986) show tendency that drying at high temperatures, lower moisture content and combine harvesting increase breakage susceptibility but differences among hybrids remain. Hybrids with higher breakage susceptibility have a higher possibility to brake during handling, which could cause nutrient loss and decreased nutritional value. Due to different instrument performances among studies, the obtained values in the present study are difficult to compare with previous ones. However, it should be noted that the drop height of the aluminium bar was chosen to provide energy for the breakage of as many grains as possible to achieve greater differences between tested hybrids. In total, 30% of tested hybrids had breakage susceptibility lower than 20%, while only 6% had values higher than 40%.

Dimensional properties of 80 hybrids tested in the present study are presented in Table 4, and kernel height was 12.34 mm, width 8.30 mm and thickness 4.97 mm on average. The obtained values are similar to other studies; for example, the average height, width, and thickness of samples in the study by Blandino et al. (2010) were 13.3 (12.4- 14.1), 8.9 (7.5-9.6) and 4.2 mm (4.0-5.2), respectively. Smaller and more rounded grains usually belong to hybrids of higher grain hardness (Paulsen et al., 2003), so dimensions in this way may indirectly indicate nutritional value. The same relationship was found for the kernel sphericity – Blandino et al. (2010) found a significant positive correlation with Stenvert grinding time and the coarse-to-fine particles in a freshly ground sample. In this study, the sphericity varied from 0.56 to 0.77.

Correlations among physical traits of tested hybrids

As in previous studies, correlations were found among the physical properties of 80 commercial high-yielding hybrids tested, and the most important are presented in Table 5. A positive correlation between the weight and volume of 1,000 kernels and the height and width of an individual kernel (P<0.001), as expected, indicates that grains of hybrids of larger kernel sizes have higher weight and volume. Blandino et al. (2010) also found a positive correlation between kernel size and 1,000 kernel weight, but in their case, it was with width (r=0.61, P<0.01) and thickness (r=0.57, P<0.01). Blandino et al. (2010) and Jennings (1974) also found that test weight decreases with kernel height and width, respectively, but increases with sphericity, which is confirmed by the results of this study (r=0.32, P<0.01). This implies that hybrids with larger kernel generally have a lower test weight in comparison to the ones with small grain.

Test weight positively correlated with density (r=0.64, P<0.001) suggesting that higher test weight naturally indicates heavier kernels with a lower volume of 1,000 kernels. The similar coefficient of correlation reported Lee et al. (2007; r=0.52, P<0.01). Both test weight and density similarly correlated with other characteristics obtained from methods related to grain hardness (flotation index and Stenvert test), confirming that these are the methods which could be used for estimation of maize grain hardness (Fox and Manley, 2009). Hybrids with grains of higher test weight and density had fewer floaters (r=-0.71 and -0.64, respectively, P<0.001), needed longer grinding to obtain 17 mL of grits (r=0.68 and 0.62, respectively, P<0.001), had lower heights of grits in collection tube (r=-0.72 and -0.67, respectively, P<0.001) and had higher coarse-to-fine particles ratio (r=0.68 and 0.52, respectively, P<0.001). The correlation coefficients are somewhat higher for test weight than for density most likely reflecting the packing effect of test weight also in hardness. Similar correlations for test weight were reported for 30 maize samples in the study by Blandino et al. (2010) and 72 commercial hybrids in the study by Harlesson et al. (2019), while Li et al. (1996) found that test weight is higher in hybrids with a higher ratio of hard to soft endosperm in the kernel (r=0.81). Results of the present and abovementioned studies show that test weight could be efficiently used in the estimation of maize hybrid kernel hardness and its nutritional value.

Although it is a method for determining specific density, the floatation index is efficiently used for the estimation of maize grain hardness (Fox and Manley, 2009). Results of this study confirmed this specific use of flotation index: hybrids with a higher number of floating kernels also are faster to grind (r=-0.68, P<0.001), have higher heights of grits in collection tube (r=0.75, P<0.001) and lower coarse-to-fine particles ratio (r=-0.65, P<0.001). Additionally, hybrids of higher kernel heights had a higher floatation index (r=0.31, P<0.01). The same finding reported Blandino et al. (2010; r=0.48, P<0.01). This positive correlation is a result of smaller and more rounded kernels in hybrids of higher grain hardness (Paulsen et al., 2003) which implies that kernel height of commercial maize hybrids could be used as an indirect measure for hardness.

Table 5. The most important correlation coefficients among determined physical properties of kernels from tested hybrids[1]

Physical trait	W_{1000}	V_{1000}	Test weight	Density	FI	Time	Height	C/F	Breakage susceptibility
Test weight	-0.14	-0.46***		0.64***	-0.71***	0.68***	-0.72***	0.68***	0.04
True density	0.03	-0.17	0.64***		-0.64***	0.62***	-0.67***	0.52***	-0.19
FI	-0.06	0.17	-0.71***	-0.64***		-0.68***	0.75***	-0.65***	0.24*
Time	-0.04	-0.25*	0.68***	0.62***	-0.68***		-0.77***	0.78***	-0.30**
Kernel height	0.40***	0.54***	-0.55***	-0.30**	0.31**	-0.48***	0.41***	-0.46***	-0.30**
Kernel width	0.47***	0.51***	-0.30**	-0.02	0.14	-0.07	0.22*	-0.11	-0.27*
Sphericity	-0.04	-0.14	0.32**	0.11	-0.11	0.22*	-0.11	0.20	0.22*
Breakage susceptibility	-0.48***	-0.45***	0.04	-0.19	0.24*	-0.30**	0.19	-0.19	

[1] W_{1000} – 1,000 kernel weight; V_{1000} – 1,000 kernel volume; FI – flotation index; Stenvert hardness variables: the time required to grind 17 mL of grits (time), column height of freshly ground 20 g of maize kernels (height) and the ratio of coarse (>0.8 mm) and fine (<0.5 mm; C/F) particles in freshly ground 20 g of maize kernels

Further correlations with the time needed to grind 17 mL of grits (r=-0.48, P<0.001), the height of grits in collection tube (r=0.41, P<0.001) and coarse-to-fine particles ratio (r=-0.46, P<0.001) confirmed kernel height as a simple estimator for maize hybrid hardness.

The breakage susceptibility correlated with traits describing kernel weight and dimensions – 1,000 kernel weight and volume and kernel height and width. Those correlations were negative (Table 5), implying that lighter kernels of smaller volume and size will brake more easily.

CONCLUSIONS

Eighty commercial high-yielding hybrids showed high variability in physical traits. The test weight ranged from 70.19 to 82.05 kg/hL while density ranged from 1.159 to 1.301 g/mL. Flotation index varied from 8 to 100% across tested hybrids while it was needed from 2.7 to 5.94 s to grind 17 mL of grits in Stenvert test resulting in the height of grits in collection tube from 77.9 to 109.1 mm and coarse-to-fine particles ratio from 0.556 to 1.754. Kernels of tested hybrids were on average 12.34 mm high, 8.30 mm wide and 4.97 mm thick resulting in sphericity of 0.64. The density was the trait with the lowest variability among tested hybrids while breakage susceptibility was the most variable trait, with a range from 7.1 to 64.88%.

The test weight and flotation index have been confirmed as simple estimators of grain hardness. Kernel height has also been shown to have the potential to estimate both test weight and Stenvert hardness. These simple methods could be used to discriminate commercial high-yielding hybrids based on hardness, as this trait is related to dry-milling performance, post-harvest resistance to insects and starch digestibility of maize.

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