Environment and production practice influence on grain quality of maize and sorghum

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Abstract

Desirable grain quality attributes vary depending upon the intended end use of grain. Environment, production practices and genetics are all of importance. Nutritional value of grain is most important for animal feed. Dry mill and alkaline cooked products require hard kernels with low breakage susceptibility and high protein concentration. Grain for these uses would best be produced under dryland conditions with abundant N supply. Wet mill starch extraction is best with soft to intermediate kernel texture, low kernel breakage susceptibility, low protein concentration and high extractable starch concentration. Grain for this use would best be produced under irrigated conditions with relatively low N supply. Grain for ethanol would require similar production environments.

Key words: kernel hardness, kernel breakage susceptibility, starch viscosity, nutritional value

Introduction

Maize and Sorghum Grain Use in the United States

Uses of grain in the United States have changed greatly with adoption of use of maize and sorghum grain for fuel ethanol production during the last 15 years (USDA-ERS/FAS, 2011). Fuel ethanol production is the largest use of maize grain, and the second largest use of sorghum grain (Table 1). Livestock feed remains an important end use of these grains with approximately equal use as feed for ruminant (beef and dairy) and monogastric (swine and poultry) animals (Capehart and Allen, 2011). Fuel ethanol by-products (distillers grains, gluten feed) have become important livestock feed sources for ruminant animals (Erickson et al., 2010), but due to the higher fiber concentration can only be fed to 30% of swine rations (Stein, 2008) and 15% of poultry rations (Bregendahl, 2008). Export markets are important for all three grains; however this is the largest end use of sorghum (Capehart and Allen, 2011). Thus, attributes associated with maintenance of grain quality through export handling and shipping in addition to those attributes desired for each end use is important.

Grain production in the United States during the past decade has split into two distinctly different paths: commodity production with emphasis on increases in farm size and grain yields to reduce per unit production cost; and production of specialty grain requiring special management practices with producers receiving a premium price. The grain handling system in the United States has been developed to handle large volumes of grain with wide spread comingling of grain from different sources and relatively minor attention to delivering superior quality grain beyond grain moisture and test weight. Due to this, specialty grain production is usually done under "buyers call" contracts with stipulations for superior quality grain. In order to meet these requirements, most grain is stored on-farm until delivery is requested by the buyer, dried without addition of heat (natural air drying), and handled with care to prevent contamination of grain. The development of these specialty grain markets has driven my research efforts to better understand the influence of environment and production practices on grain quality for use as dry-milled and alkaline-cooked food products, wet-milled starch extraction and for maintenance of quality during handling and shipping. In addition, efforts have been made to extrapolate the information generated to livestock feed and fuel ethanol production.

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Table 1. Utilization of maize, sorghum and wheat grain in the United States, 2009-2010.

Crop	Livestock Feed,%	Dry Mill (Human Food),%	Wet Mill (Starch),%	Fuel Ethanol,%	Export,%
Maize	37	2	8	40	13
Sorghum	35			24	42

Source: Capehart and Allen (2010)

Table 2. Attributes desired for different end uses of maize and sorghum grain.

Monogastric Feed	Ruminant Feed	Wet Mill (Starch Extraction)	Dry Mill and Alkaline Cooked Food Products	Fuel Ethanol
High Digestible Energy (Starch, Lipid)	High Digestible Energy (Starch, Protein, Fiber, Lipid)	High Extractable Starch	Hard Endosperm	High Fermentable starch
High Starch Concentration	Rapid, But Not Too Rapid Starch Digestion (Acidosis)	Intermediate or Soft (Uniform Steeping)	Low Breakage Susceptibility (Brittleness)	High Starch Concentration
High Lipid Concentration	High Mineral Concentration	Low Breakage Susceptibility and Stress Cracks	Low Percentage Stress Cracks	Low Kernel Breakage
Essential Amino Acid Concentration and Bioavailability		Starch – Protein Density Differences (Protein – Starch Separation)	Easy Pericarp Removal	Low Protein Concentration
High Mineral and Vitamin Concentrations and Bioavailability		Low Protein	Low Mycotoxin Concentrations	Protein Easy to Degrade
Low Mycotoxin Concentration		High Lipid		

Desirable Grain Characteristics

Desirable grain attributes for livestock feed are primarily nutritional, largely physical properties for dry milling and alkaline cooked products, and characteristics related to starch separation/fermentation for wet milling and fuel ethanol uses (Table 2). Grain is largely fed to livestock as an energy source, which mainly comes from starch which makes up approximately 70% of the grain endosperm. Other energy sources include lipid which is largely present in the germ, and for ruminant animals, also fiber and protein. In the rumen of ruminant animals, starch, protein and fiber are broken down into volatile fatty acids which are taken up as the primary energy source. If starch is digested too rapidly, the rumen pH decreases creating acidosis which reduces animal uptake of feed (or in extreme cases leads to death), however if the starch is too resistant to digestion then it passes through the digestive system. Bacteria in the rumen manufacture high quality bacterial protein and water soluble vitamins which are digested and taken up in the small intestine. Rumen activity also reduces problems with mycotoxins and increases bioavailability of minerals. In contrast, monogastric animals require a balance of the 10 essential amino acids, and adequate levels of vitamins and minerals in the diet, and are quite susceptible to the presence of mycotoxins in feed.

In dry milling, the grain is tempered to facilitate removal of the pericarp and germ. The germ provides a high-valued oil by-product, and lipid removal increases the palatability and storability of food products made from the endosperm. For maize, the high value products are grits (large pieces of endosperm) used to make breakfast cereals and also as an adjunct in beer fermentation. Meal and flour are used for baking and other food products, but these products are of much lower economic value. Although dry-milled products are largely used to make human food products, the nutritional value is of relatively small economic importance, thus the physical properties of the grain are usually most important. Hard endosperm grain with low percent stress cracks and low kernel breakage susceptibility is desired (Shandera et al., 1997). Since food products are consumed by humans, a low level of mycotoxins is important. Alkaline cooking to make Central America food products is a very different process than dry milling, but the same desired grain quality attributes as dry milling, plus easy pericarp removal is important for sheeting of tortillas (Johnson et al., 2010).

In wet milling, the grain is steeped, germ removed and the remaining components of the grain are ground, screened to remove the pericarp, and centrifuged to separate the protein and starch. The lipid is removed from the germ as a high value by-product, and the protein separated from the starch is also a high value by-product used as a component of pet food. Uniform steeping is important to produce a high percentage of extractable starch, so low percent stress cracks, low breakage susceptibility and having soft to intermediate endosperm hardness is important. Low percent protein with large density differences between the protein and starch assists with separation of the starch and protein. Desired attributes for fuel ethanol production are similar to wet milling, except a high percent fermentable starch, rather than extractable starch, with low protein concentration (Fox et al., 1992) that degrades easily during fermentation allowing liberation of the starch for fermentation to take place.

Grain hardness is commonly measured by bulk density (test weight), true density and tangential abrasive dehulling device (TADD) removal, and the Stenvert hardness test; and grain breakage susceptibility (brittleness) using the Wisconsin breakage tester and/or counting visible stress cracks of grain on a light table. Nutrient analysis provides base information about nutritional value of grain, but the actual performance of animals provides a more comprehensive evaluation. Research finding using these procedures will be presented below to document the influence of environment and production practice on grain quality, and related to the desirable attributes for different end uses.

Environment and Production Practice Influence on Grain Hardness and Brittleness

Environment – Year, Location and Water Regime

The most comprehensive study on environment influence on grain hardness was conducted with grain sorghum across 12 production environments in Nebraska (Griess et al. 2010). Variation indicated that environment had a 60+ times greater effect on kernel hardness than genotype and that the environment by-genotype interaction accounted for less than 2% of the total variation. Bulk and true densities were greater and TADD removal less in 2005 than in 2004 (Table 6) indicating harder kernels were produced in 2005. This was likely due to warmer temperatures and higher potential evapotranspiration in 2005 than in 2004, consistent with other research that has shown production of harder kernels when more water and/or heat stress is present (Johnson et al, 2010; Taylor et al., 1997). Similar results have been reported for maize (Bauer and Carter, 1986; Kniep and Mason, 1989).

Eastern Nebraska Dryland with Low N environments in 2004 and 2005 produced kernels that were less dense than other environments, more so in 2004 when N was more limiting than in 2005. This environment also had the lowest bulk density and highest TADD removal. West Central Nebraska and Central Nebraska - Hebron Dryland environments in 2005 produced kernels with the smallest TADD removals (i.e. hardest kernels). These two environments had the highest average temperatures in August, during the early grain fill growth stage. Dryland environments produced grain with greater bulk density, but similar true density and TADD removal with irrigated environments. Other research with sorghum and maize has shown that kernel density is greater under dryland conditions than irrigated conditions, and that increased N rate increases kernel density (Taylor et al., 1997; Kniep and Mason, 1989; Bauer and Carter, 1986; Duarte et al. 2005). Johnson et al. (2010) found harder sorghum kernels produced under hotter and drier Texas growing conditions than in Kansas and Nebraska.Kniep and Mason (1989) and Bauer and Carter (1986) studied year and water regime influences on maize hardness and breakage susceptibility. Averaged across three years, irrigation (with higher plant populations) increased the kernel breakage susceptibility and decreased the true density, indicating that irrigation resulted in production of softer, more brittle grain. Only small year effects were found. Duarte et al. (2005) also found only small differences in grain hardness and breakage susceptibility across two dryland environments and years in Brazil.

Nitrogen Supply, Crop Rotation and Cultural Practices

Nitrogen fertilizer application is usually required to optimize maize grain yields and tends to improve the physical grain quality in maize by increasing kernel weight and density (Bauer and Carter, 1986; Kniep and Mason, 1989), and protein and zein concentrations (Oikeh et al., 1998; Manokumar et al., 1978) while decreasing breakage susceptibility (Kniep and Mason, 1989). Increasing N supply to maize plants increases zein concentrations in the endosperm, thus creating harder and more translucent grain (Tsai et al., 1984;

Tsai et al., 1992). Duarte et al. (2005) found that increasing N rates from zero to 180 kg ha^{-1} increased grain yield, protein concentration, Stenvert hardness test results while reducing TADD removal and breakage susceptibility of grain produced in three Brazilian production environments. Kniep and Mason (1989) and Sabata and Mason (1992) found that increasing N rates increased true density and reduced kernel breakage susceptibility of maize grain.

Kaye et al. (2007) studied the influence of soybean crop rotation, manure and N application on the grain quality of sorghum. Nitrogen supply increase, whether from rotation with soybean, manure or fertilizer, increased the grain protein concentration greatly, test weight and true density by a small amount, while decreasing the TADD removal greatly. They concluded that crop rotation, manure and fertilizer application altered grain hardness, and are important factors to produce grain with desirable quality attributes for dry milling and alkaline cooking products. Griess et al. (2010) found that low N application reduced sorghum yield and grain hardness. When N supply was intermediate, grain produced was soft with high starch concentration and low protein concentration, ideal grain quality for ethanol fermentation.

In addition to N supply, Bauer and Carter (1986) studied the effects of plant population and delayed planting on breakage susceptibility. They found that each 10-day delay in planting date increased breakage susceptibility by 1.6%, and for each 2.0 plant m^{-2} increase in plant population breakage susceptibility increased 1.5 to 2.0%.

Grain Drying

Although extreme grain handling can result in production of stress cracks leading to breakage, grain drying is by-far the most important. Research has shown that drying grain at high temperatures (Paulsen et al., 1983; Weller et al., 1990; Gunasekaran and Paulsen, 1985), with high moisture concentration (Weller et al., 1990), and cooling dried grain rapidly (Kim et al., 2002) are the major causes of formation of stress cracks which with handling lead to breakage. Little relationship between breakage susceptibility and grain hardness occurs unless stress cracks are already present, and then breakage susceptibility is greater for hard than soft kernels (Weller et al., 1988).

Environment and Production Practice Influence on Starch Viscosity Properties and Extractable Starch

Rapid Visco Starch Analysis (RVA) relates biochemical components to grain hardness (Fox and Manley, 2009; Almeida-Dominguez et al., 1997). This method measures the viscosity developed during hydration and subsequent gelatization of starch granules during heating and stirring in excess water (Almeida-Dominguez et al., 1997), including pasting temperature when gelatization begins and the peak viscosity at full gelatinization (Fig. 1). When held at maximum temperature and stirred, the starch molecules become oriented (shear thinning) and the viscosity declines to the trough viscosity (holding strength). The difference between peak and trough viscosity is termed breakdown viscosity. These starch viscosity properties help predict the functionality of food products. High peak, final and setback viscosities have been associated with high ethanol yield from sorghum grain (Zhao et al., 2008), high pasting temperature with the need for intensive cooking to produce high consumable alcohol yields (Agu et al., 2006), and low peak viscosity with softer endosperm grain, having greater expansion during cooking, and production of less-stiff porridge (Taylor et al., 1997).

Griess et al. (2011) studied rapid visco starch analysis (RVA) properties of sorghum grain produced by 16 genotypes in 12 environments. Environment, genotype and environment-by-genotype interaction effects were present for all RVA parameters. However, environment accounted for 71 to 85% of the total variation, hybrid accounted for 11 to 23% and the environment-by-genotype interaction for only 1 to 3%. Protein concentrations were greater in more stressful production environments (i.e. low N and water limiting), while starch concentrations were higher in less stressful production environments (i.e. moderately limiting to adequate N, irrigated) consistent with the expected inverse relationships between protein concentration and starch (McDermitt and Loomis, 1981; Kaye et al., 2005).

Identifying environments producing grain with consistent cooking and pasting properties would require food processors to make only minor adjustments to maximize the quality of the final product (Tester and Karkalas, 2001). All viscosity parameters and pasting temperature of grain had a wide range across environments, while the variation in peak time was less. Peak and breakdown viscosities were greater for grain produced in 2004 than in 2005, while all other RVA parameters were greater for grain produced in 2005. The 2005 growing season had higher temperatures and potential evapotranspiration than 2004, and produced more dense grain (Griess et al., 2010), and starch concentrations were lowest. Peak and trough viscosities, pasting temperature and starch concentration of grain were greater under irrigated than under dryland water regimes, consistent with the results of Taylor et al. (1997).

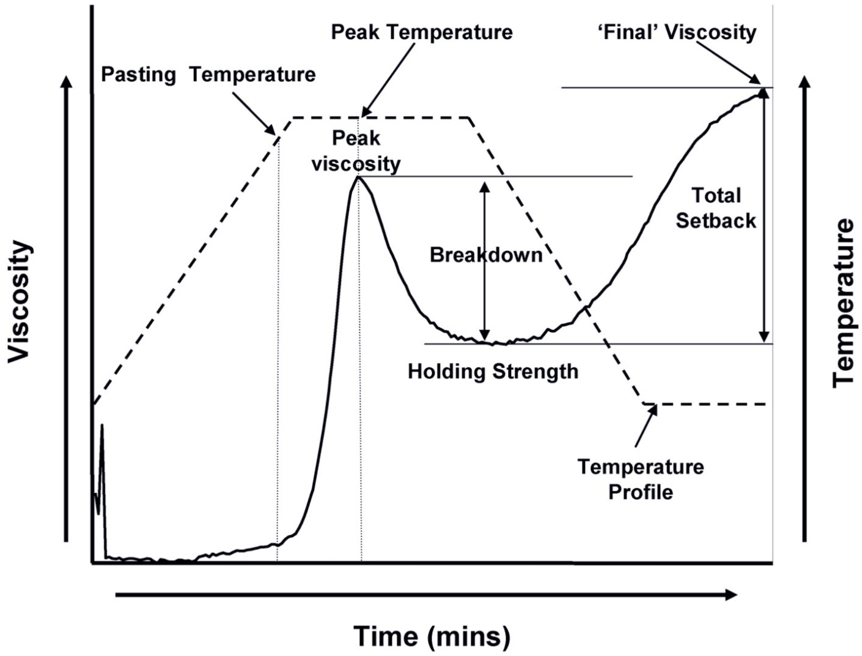

Figure 1. Rapid Visco Starch Analysis (RVA) profile (Adapted from Agu et al., 2006).

The West Central Nebraska 2005 environment, the most stressful environment, produced grain with high protein and low starch concentrations, and the lowest peak, trough, breakdown, final and setback viscosities, and relatively high peak time and intermediate pasting temperature (Griess et al., 2011), and produced the densest grain (Griess et al., 2010). This indicated that starch granules in the flour from this environment hydrated more slowly due to the thick protein matrix surrounding the starch granules, took longer to gelatinize, the flour slurry was less stable during shear-force thinning, and aligned starch molecules did not re-associate well with each other. Grain produced in this environment would therefore be well suited for food products made by dry milling (Shandera et al., 1997) or alkaline cooking (Almeida-Dominguez et al., 1997; Johnson et al., 2010).

In contrast, the Central Nebraska - Hebron Dryland 2004, Central Nebraska - Clay Center irrigated 2004, and Eastern Nebraska Dryland Low N 2005 environments produced grain with the highest peak, trough, breakdown and final viscosities, and high setback viscosities, and low pasting temperatures (Griess et al., 2011) These environments produced grain with low protein concentrations and soft kernels (Griess et al., 2010). These results suggest that these three environments produced grain useful for processed and canned products (Beta et al., 2000), porridge (Taylor et al., 1997), fuel ethanol (Zhao et al., 2008; Wu et al., 2007) and/or consumable alcohol (Agu and Palmer, 1998, Agu et al., 2006).

Few studies have been conducted specifically to study the effects of environment or production practices on extractable starch, the high-value end product of wet milling. Mason and D'Croz-Mason (20002) reported that the greatest extractable starch differences of were due to year, while 1.6% difference was due to hybrid, 1.0% due to plant population and 0.3% due to water regime. High plant populations, irrigation and high rainfall years increased the extractable starch production.

Environment and Production Practice Influence on Nutritional Value - Protein and Amino Acid Balance

Environments and production practices that result in high grain yields also produces grain with high starch concentration and low protein concentration (McDermitt and Loomis, 1981). This inverse relationship between yield and protein concentration has been shown for maize (Vyn and Tollenaar, 1998; Duarte et al., 2005; Kniep and Mason, 1991; Sabata and Mason, 1992; Mason and Sabata, 1995) and sorghum (Kaye et al., 2005; Griess et al., 2010; Griess et al., 2011). The negative relationship between protein concentration and grain yield is partly associated with the higher glucose cost for synthesis of protein than carbohydrates (Penning de Vries et al, 1975).

Nitrogen supply increases due to fertilizer or manure application, or crop rotation with a legume increase grain and protein yields, and often increase the protein concentration of maize (Kniep and Mason, 1991; Sabata and Mason, 1992; Tsai et al., 1983; Tsai et al, 1992; Duarte et al., 2005) and sorghum (Kaye et al., 2005; Griess et al., 2010; Griess et al., 2011). Tsai et al. (1983) suggested that protein concentration of maize grain increases with N supply due to preferential deposition of zein over other endosperm proteins. Higher N rates are required to maximize grain protein concentration than grain yield (Sander et al., 1987).

As the protein concentration of maize increases, the protein zein makes up an increasing proportion of the protein (Tsai et al., 1992) leading to grain that is harder, less brittle and more translucent. Likewise in sorghum, the protein kafrin makes an increasing proportion. Since zein and kafrin proteins have low concentrations of the limiting essential amino acids lysine and tryptophan, the biological value of the protein is decreased. Kniep and Mason (1991) found that irrigation increased maize grain yield, reduced protein concentration, and increased the percent lysine of protein. Increased N supply increased grain yield, protein concentration and reduced percent lysine of protein. The grain from this study was used in a rat feeding study, and found that rats fed grain from irrigated plots had greater and more efficient rates of gain, while those fed grain with high N supply had lower and less efficient rates of gain (Hancock et al., 1988). Irrigation appears to have a positive effect on maize grain amino acid balance, while N supply has a negative effect (Mason and D'Croz-Mason, 2002) on the essential amino acid concentrations of lysine, tryptophan, and threonine (Rendig and Broadbent, 1979).

Conclusion

Grain yield is important for all end uses of grain, as this ultimately influences the cost per unit of feedstuff or feed stock for all end uses. If yield is equal, then the presence of the desired quality grain attributes becomes of utmost importance in producing high-value end products of meat, meat and eggs; starch; dry mill and alkaline cooked food products; and fuel/consumable alcohol. Environment is the largest factor influencing grain quality, but production practices and genetics is also of importance.

For monogastric animals, the key is to produce grain with high amounts of digestible starch and oil, and a balance of essential amino acids. In general, this is best accomplished with irrigation and a relatively low N supply, which produces a less dense, more digestible grain with better amino acid balance. Ruminant animals have less exacting requirements due to fermentation of feedstuffs in the rumen. Highest rate of gain occurs with soft grain that digests completely and rapidly, however, if starch is digested too rapidly, acidosis can reduce gains and in extreme cases, lead to animal death.

Dry mill and alkaline cooked products require hard kernels with low breakage susceptibility, which are correlated with high protein concentration. Ideally grain for these uses would be produced under dryland conditions with abundant N supply. Wet mill starch extraction is best with softer kernel texture, low kernel breakage susceptibility, low protein concentration and high extractable starch concentration. Ideally this grain would be produced under irrigated conditions with relatively low N supply. Fuel and consumable ethanol would require similar production environments to wet milling, but in this case, the key is liberation of starch from the protein matrix so that fermentation can occur. For all end uses, the grain should be dried with natural air or very low heat in order to minimize production of stress cracks and thus, increasing kernel breakage susceptibility. Breakage susceptibility generates dust which is harmful to animals, causes uneven steeping in wet milling and alkaline cooking, loss of product in screening before milling and ethanol production, all reducing the quantity of high value product produced. Transportation of grain through the export stream is a physically demanding process, thus production environment, grain drying and handling, and genetics are all important to produce grain that maintains integrity throughout the export channel.

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