Impact of Starch Source and Processing on Feedlot Production with emphasis on high-moisture corn

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Grain feeding in beef finishing programs was documented as early as 1898 by W.A. Henry (as cited by Albin et al., 1996): "*Indian corn must continue the great grain food for steer fattening in the United States…The success of steer feeding in America must depend largely upon the supply of Indian corn available for this purpose*." The cattle feeding industry has changed since that time becoming a highly industrialized, dynamic, aggressive, and highly technical agribusiness (Albin et al., 1996), but corn grain still comprises the majority of most feedlot diets. Central to advances in feedlot technology has been the ability to formulate economical energy dense diets for cattle through feeding grains and high-starch byproducts at high inclusion levels. Although grains are widely fed and are extremely nutritious, opportunities still exist to improve their utilization by cattle. By altering both site and extent of digestion, proper grain processing can maximize the net energy value of corn grain.

Starch from well-processed grain is highly digestible, but even minor improvements in utilization can impact production efficiency. Based on the Metabolizable Energy content of starch estimated by (Kellner, 1919), the net energy for gain of starch is 1.88 megacalories per kilogram (NRC, 1996). Huntington (1997) indicated that dry-rolled corn has a total tract starch digestibility of 92.2%. On this basis, a 1% improvement in digestibility of a beef finishing diet would provide 0.05 kilograms more starch and 0.10 megacalories additional Net Energy for Gain. Assuming that roughly 5.43 megacalories of Net Energy for Gain is required for 1 kilogram of body weight gain (Lofgreen and Garrett, 1968), this 1% increase in diet digestibility would result in a 0.6% improvement in Average Daily Gain and a 0.9% improvement in feed efficiency (Feed:Gain) and in Cost of Gain (all other things being equal). Considering that feedlot steers typically gain 273 kilograms during the feeding period, a 1% improvement in starch utilization potentially can increase profit by $2.80 per head. Therefore, even small modifications in starch digestibility will impact profitability. This can explain the broad research and commercial interest in improving utilization of starch.

Factors Influencing Starch Utilization

Starch Chemistry

Starch utilization by feedlot cattle varies with the type of grain fed and its genetic traits, the maturity of the grain at harvest, the agronomic conditions under which the grain was grown, and the method of grain processing. Genetic traits, agronomic conditions, and maturity at harvest all can alter starch chemistry and/or endosperm texture. Distribution of starch in the endosperm can have an impact on digestibility. Furthermore, variation in starch hydrolysis across cereal grains can be explained partially by differences in starch granule structure (Davis and Harbers, 1974). For example, waxy grains, because of their high degree of branching associated with greater amylopectin content, results in improved starch utilization (Mohd *et al*., 1984) unless grains are well processed. Amylose is a linear polymer while amylopectin has branch points every 24 to 30 glucose units. Such branching disrupts the starch molecule creating amorphous regions that are more susceptible to enzymes. In contrast, linear amylose components retard alpha amylase hydrolysis of the starch granule (Leach and Schoch, 1961 as cited by Kimura and Robyt, 1995). Nevertheless, information regarding the impact of feeding waxy grains has been inconsistent. For grains with a low inherent digestibility (e.g., rolled sorghum), feeding waxy grains appears to be beneficial. Wester *et al*. (1992) ranked 48 commercial grain sorghum hybrids based on *in vitro* starch disappearance (**IVSD**). Among these samples, three hybrids had similar genetic background but differed in genetic coding for amylopectin content. The waxy hybrid was found had the fastest rate of IVSD while the non-waxy hybrid had the slowest rate of IVSD. Finishing steers fed the high IVSD sorghum diet gained weight 9% faster than steers fed the slow IVSD sorghum. Moreover, Gain:Feed for steers was correlated positively with IVSD ($r = 0.94$). Although amylopectin content appears to be an important consideration in sorghum, waxy corn has not proven to provide improved finishing performance as compared to typical corn that contains 24 to 30% amylose. Since cornstarch inherently is more digestible (i.e., less disulfide crosslinking) than sorghum starch, presence of the waxy trait has less potential to improve starch availability and animal performance with corn than with sorghum grain (Stock, 1999).

Differences in the digestibility of isolated starch granules by amylases can be attributed partially to degree of crystallinity (Manners, 1985 as cited by McAllister *et al*., 1993). Gelatinization disrupts starch crystallites thereby improving starch availability. Accordingly, grain processing methods that capitalize on this reaction often are employed. Steam flaking is one method whereby grains are partially gelatinatized by steam under atmospheric pressure for a designated amount of time (typically 30 to 60 minutes at 100 to 105^{o} C) and then rolled. Galyean *et al*. (1976) reported that ruminal starch digestion was greater for steam-flaked compared to dry-rolled corn (82.9 versus 77.8%, respectively). Huntington (1997) noted that steam processing increased ruminal starch digestibility of sorghum 33% over dry rolling. In a thorough review, Zinn *et al*. (2002) summarized data from 64 trials, and concluded that steam flaking increased ruminal digestibility of starch in corn grain by 12.7 to 45.8% compared to dry rolling.

These studies indicate that steam flaking increases starch digestibility due primarily to gelatinization. Retrogradation, or the realignment/reassociation of starch molecules from an amorphous state back to a semi-crystalline state, occurs after heating. One practical example of retrogradation is the staling of bread. Retrogradation causes a glue-like hardening during slow cooling of affected segments of amylose starch; this decreases porosity of the internal starch matrix and limits rehydration and enzyme penetration (Zinn and Owens, 1986). Therefore, steam-flaked corn that is held warm may retrograde; this, in turn, theoretically should decrease starch availability relative to fresh steam-flaked corn. However, Zinn and Barrajas (1997) noted similar starch reactivity and total tract digestibility between fresh steam-flaked corn and steam-flaked corn allowed to dry naturally for 5 days. Unlike the drying procedures used by Zinn and Barrajas (1997), most mills supplying steam-flaked corn to dairy operations artificially remove moisture using commercial grain dryers. Presumably, artificial drying may impact degree of retrogradation. Nevertheless, Ward and Galyean (1999) and Fred Owens (personal communication) have observed that susceptibility of starch to amylopectin hydrolysis was retarded following slow cooling of flaked corn grain. Ward and Galyean (1999) found that *in vitro* dry matter disappearance for flaked grain with the lower starch availability was no lower than that for the flaked grain with a higher starch availability. Consequently, retrogradation may not markedly alter rate or extent of starch digestion *in vivo*.

Endosperm Texture

Yellow **dent** corn is the result of a cross between **flint** (**vitreous**) hybrids and soft endosperm hybrids. Dent grain indents at the top when the soft internal starch shrinks as the kernel dries. Prevalence and depth of dent appears greater for softer hybrids. Pure flint hybrids are still produced in South America and Europe despite their yield drag. Within North America, shorter season hybrids typically have more flint genes, perhaps because of a genetic linkage with other genes that increase cold tolerance of the seedling.

Endosperm texture can impact utilization of starch. Vitreous regions of endosperm have starch granules surrounded by protein storage bodies and a dense matrix of endosperm cells (Watson, 1987 and Philippeau, *et al*., 2000). As a result, the vitreous endosperm partially resists physical and enzymatic degradation. In contrast, when the kernel matures and dried, weakness of protein linkage allows starch granules to separate in floury endosperm leaving little intra-cellular structure; air spaces between the starch granules results in a lower absolute density for floury than for vitreous starch (Kotarski *et al*., 1992; Philippeau, 2000). Floury dent hybrids generally have a lower bushel weight than more vitreous dent corn hybrids but kernel size, shape, maturity, and pericarp slickness also can influence bushel weight. Some differences in starch utilization can also be attributed to variations in endosperm type. For instance, sorghum grain has been suggested to have a greater proportion of vitreous endosperm (Rooney and Pflugfelder, 1986), and starch from sorghum grain when dry-rolled has lower total tract starch digestibility compared to corn (87.2 versus 92.2%, respectively; Huntington, 1997). Spicer *et al*. (1986) fed diets containing approximately 80% dry-rolled sorghum, corn, or barley. Compared to sorghum grain, ruminal and total tract starch digestion were 11.3 and 2.0% greater for corn, respectively. However, when flaked, starch digestibility of sorghum grain, like corn grain, usually exceeds 98% (Fred Owens, personal communication).

Corn containing a greater proportion of vitreous endosperm (flint) has lower ruminal starch availability relative to floury corn based on both *in situ* and ruminal measurements. Correa *et al*. (2002) compared corn hybrids that differed in degree of vitreousness (34.9% to 80.0%); ruminal *in situ* starch availability was negatively correlated with kernel vitreousness (r = 0.87). Starch vitreousness increased and ruminal *in situ* fermentability decreased as the kernels matured. The decrease in ruminal *in situ* starch fermentability with advancing maturity was greater for grain from a more floury endosperm than for grain from a more vitreous endosperm. Philippeau and Michalet-Doreau (1997) characterized corn by endosperm traits and reported that ruminal *in situ* starch degradability was negatively correlated with kernel vitreousness (r = 0.86). Much of the difference in starch disappearance associated with vitreousness was fraction *a*, the material lost during washing of the *in situ* bags in water that would consist of small particle and soluble starch. However, in a subsequent study, Philippeau *et al*. (1999) reported further that ruminal starch digestibility with rolled grain was greater for floury (dent) compared to flint hybrids (60.8 versus 34.8%, respectively). When evaluating the effect of kernel processing on corn silage hybrids (Pioneer 3845 and Quanta) differing in endosperm type, Johnson *et al*. (2002)

noted that degree of vitreousness influenced total tract starch digestion slightly. Furthermore, kernel vitreousness explained 17% more of the variation in starch digestibility for unprocessed corn silage; this indicates that processing disrupts the vitreous endosperm sufficiently for digestion to occur. This suggests further that grinding vitreous grain to a very small particle size may alleviate the starch digestibility depression associated with more vitreous corn kernels.

Implication of Protein on Endosperm Texture

Philippeau *et al*. (2000) collected data from 6 flint and 8 floury dent corn hybrids; they reported that the two classes of hybrids had similar starch content (mean = 67.5%) but differed markedly in their proportions of vitreous starch (71.8 versus 51.4%, respectively). Additionally, total zein content was positively and glutelin content was negatively correlated with degree of vitreousness; the amount of true glutelins was greater for dent than flint hybrids (21.8 versus 18.4% of CP, respectively). These findings are not novel. Wolf *et al*. (1952) reported that protein bodies were larger for vitreous compared with floury endosperm, and Dombrink-Kutzman and Bietz (1993) observed greater proportions of total zeins in hard endosperm fractions than in soft endosperm fractions. This association is important because core bodies of endosperm protein complexes are thought to be comprised of one or more of the zein proteins (Christianson *et al*., 1969). Ruminal starch degradability is negatively correlated with the amount of certain zeins but positively correlated with the amount of glutelins, but whether the proteins are involved directly or indirectly through altering particle size distribution of the ground grain is not fully clear.

McAllister *et al*. (1993) demonstrated that barley and corn starch granules did not differ in digestion when the granules isolated from their protein matrices. Gas production was greater for starch granules isolated from sorghum grain than from corn during incubation with starch digesting enzymes and yeast in studies by Streeter *et al*. (1993). Because isolation of starch granules from grain may result in an enriched concentration of granules from the soft starch region, composition and digestibility of starch granules may differ from that of grains containing both soft and vitreous starch regions. McAllister *et al*. (1990) demonstrated that amylolytic bacteria were capable of digesting starch granules but not the protein matrix within vitreous endosperm; however, other bacterial species readily digested the protein matrix in barley and wheat. This indicates that zein proteins can impose limits to accessibility of starch granules. Zein contains only very low amounts of lysine and tryptophan, often the first and second limiting amino acids in corn-soy diets for swine. Plant breeders have identified corn grain with higher concentrations of lysine. Zein proteins are encoded by genes expressed during endosperm development and can be modified by gene mutations. Opaque-2 is a recessive mutant that reduces zein accumulation and a commensurate increase in alternative proteins (albumin, globulin, and glutelin) and AA (lysine; Cronje, 1985). If zein protein limits utilization of starch, Opaque-2 corn should have improved starch digestibility. Dado and Beek (1998) compared starch utilization of corn grain from high-lysine and conventional hybrids. Corn grain from seven, high-lysine and one, typical-lysine hybrid that were harvested at the black layer stage of maturity. In vitro starch digestibility after 6 h of incubation was 42.7% greater for high-lysine compared to conventional corn (55.8% and 39.1%, respectively). Even when grains were coarse-ground, IVSD after 6 h of incubation was 48% greater for Opaque-2 compared with conventional corn (70.6 vs. 47.7%, respectively). Ladely *et al*. (1995a) also conducted a series of trials aimed at evaluating the value of Opaque-2 relative to its isogenic counterpart. *In situ* rate of starch disappearance was 32% faster in Opaque-2 corn compared to typical corn (4.1 versus 3.1%/h, respectively). Furthermore, total tract digestibility of starch was 5% greater for Opaque-2 compared to typical corn (96.5 versus 91.9%, respectively). In the same study, calves fed the high-lysine corn diet gained 10.8% more efficiently than calves fed the typical corn diet (0.175 versus 0.158 gain:feed, respectively). Opaque-2 corn is characterized by a soft endosperm with loosely packaged starch granules that may be more accessible by microorganisms during fermentation (Han and Steinberg, 1989 as cited by Dado and Beek, 1998). Results from studies investigating digestibility and feeding value of Opaque-2 corn tend to parallel those comparing corn grains differing in endosperm type. As such, these data support the notion that availability of starch is influenced by type and complexity of the protein matrix. As starch type and content of zeins both can alter particle size of the ground grain, prevalence of fine, floury starch granules may explain the difference in starch availability.

Relationship between Processing Method and Endosperm Texture

Processing may negate the negative impact of a vitreous endosperm texture on starch. Researchers at the University of Nebraska (Macken *et al*., 2003) fed feedlot steers diets based on floury or vitreous corn with corn endosperm type factorial zed with processing method (i.e., dry-rolled or high-moisture). When corn grain was dry-rolled, cattle fed diets, feed: gain was superior for floury corn (Figure 1); however, when the corn grain was harvested as high-moisture grain and ensiled, feed: gain ratios were identical for steer fed floury and vitreous corn! Clearly, endosperm type interacted with processing method for the hybrids tested in this study.

An important advantage for ensiled high-moisture corn is its greater feeding value when compared to dry-rolled corn; often it is equal the feeding value of steam-flaked corn. Ladely *et al*. (1995b) fed beef steers diets containing 83% dry-rolled or high-moisture corn; IVSD rate was 76% greater for high-moisture than dry-rolled corn. Stock *et al*. (1987), testing the effects of grain combinations, noted that starch digestion of finishing diets containing high-moisture corn was 4.3% greater than for diets based on dry-rolled corn. In a similar study, Stock *et al*. (1991) reported that starch digestibility responded linearly to level of dietary high-moisture corn; diets containing high-moisture corn as the sole grain source had an average 8.9% of greater starch digestion than diets containing only dry-rolled corn.

Figure 1. Impact of corn endosperm texture and processing method on Feed:Gain in feedlot steers (Macken *et al*., 2003). Endosperm type by corn processing method interaction detected (*P* = 0.01). a,b,c = means bearing unlike letters differ (*P* < 0.10).

In diets containing wet corn gluten feed, Scott *et al*. (2003) noted a 59.3% reduction in fecal starch concentration when dry-rolled corn was replaced with high-moisture corn. When evaluating diets containing 82% corn, Cooper *et al*. (2002) observed ruminal and total tract starch digestibilities were 19.8 and 2.7% greater for high-moisture than for dry-rolled corn diets. Additionally, amount of starch digested in the rumen and total tract were not different between high-moisture and steam-flaked corn. Benton *et al.* (2005) measured, among other things, *in situ* dry matter degradability (**ISDMD**) of dry-rolled, high-moisture, and reconstituted ensiled corn. 'Low' and 'High' moisture levels were evaluated within high-moisture and reconstituted ensiled treatments. Results indicated that, compared to dry-rolled corn, high-moisture corn and reconstituted ensiled dry corn both had greater ISDMD (Figure 2). Furthermore, when moisture was increased for high-moisture (from 24% to 30%) and reconstituted ensiled (from 28% to 35%) corn, total ISDMD increased. The greatest changes in ISDMD occurred in the first 28 days of ensiling, with the greatest increase for higher moisture reconstituted ensiled corn (i.e., **35RECON**), followed by higher moisture high-moisture corn (i.e., **30HMC**), and then for the lower moisture reconstituted ensiled corn (i.e., **28RECON**). These results these would suggest that the changes in ISDMD are due to the effects of moisture and ensiling.

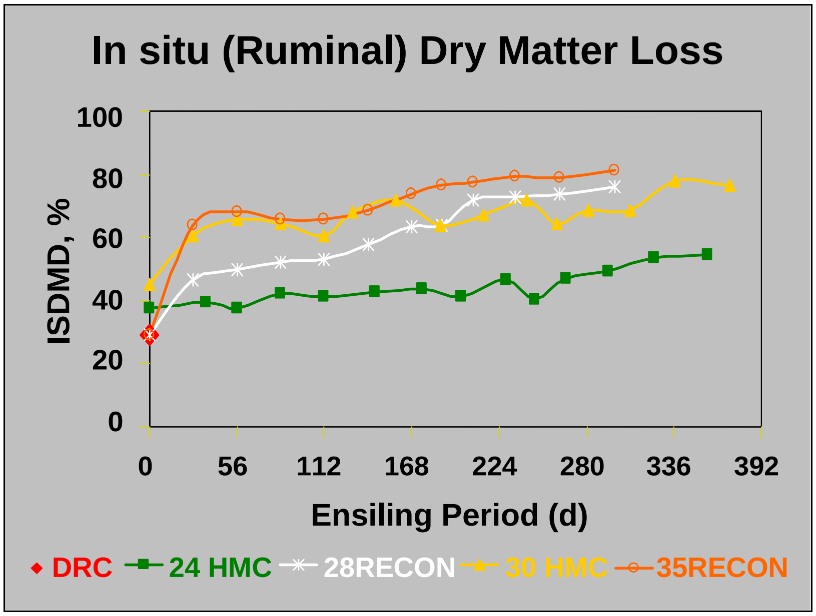

Figure 2. Impact of corn processing method and ensiling period on *in situ* dry matter disappearance (**ISDMD**; Benton *et al*., 2005).

One logical question to ask is what occurs during the ensiling process that causes starch digestibility to increase? Ensiled corn is fermented and is preserved as long as oxygen is absent. Preservation through ensiling involves three phases: 1) aerobic, 2) fermentation, and 3) stable. Initially, "wet" corn is packed into an oxygen-limiting structure. High silage density is desired to forcing oxygen from the ensiled mass. Inevitably, some oxygen remains. With oxygen, aerobic microorganisms respire plant sugars forming carbon dioxide and water while generating heat. Accordingly, the initial step is referred to as the aerobic phase. Aerobic conditions are undesirable because sugars are lost as gas and heat rather than being conserved. Undeterred, aerobic bacteria utilize soluble sugars as long as oxygen is present. In addition to sugar degradation, proteolysis continues with proteolytic enzymes from the plant and microbes reduce plant proteins to amino acids plus ammonia. Research with corn silage has indicated that proteolysis is largely a result of plant enzymes that are released with breakdown of cell membranes (Bergen *et al*., 1974 and Soderlund, 1995).

With corn silage, up to 50% of total plant protein can be degraded during this process (Holland and Kezar, 1995). With high-moisture corn, Phillip *et al*. (1985) and Baron *et al*. (1986) as cited by Buchanan-Smith *et al*. (2003) noted that at least 40% of crude protein was soluble in water (ensiled at 33% moisture). This agrees with results of Bergen *et al*. (1974) who reported water soluble nitrogen increased from 13.2% before ensiling to 41.6% at 20 days of ensiling. The Beef NRC (1996) indicates high-moisture corn has approximately 10% crude protein, 40% of which is soluble. In contrast, most of the protein in dry corn is NOT soluble in water (30% of crude protein; Van Soest, 1982). Ensiling increases protein solubility by 34 to 67%. This aspect of the ensiling process appears key to answering to why grain starch digestibility is improved by ensiling. Solubilization of the protein matrix surrounding starch granules appears to improve availability, as starch molecules become more accessible to enzyme attack (Ladely *et al*., 1995a). Galyean *et al*. (1981) and Stock *et al*. (1991) proposed this concept based on observed differences in starch availability between high-moisture and dry corn. Szasz *et al*. (2005,2006) harvested floury and vitreous high-moisture corn at different harvest dates resulting in high-moisture corn having different kernel moisture contents, and found that solubility of protein was correlated with ruminal dry matter (r = 0.89; $P < 0.02$) and organic matter (r = 0.79; $P = 0.06$) digestibility (data not shown). Solubilization of protein may increase with storage time and kernel moisture at ensiling. As mentioned previously, Benton *et al*., (2005) noted that when moisture was increased for high-moisture (from 24% to 30%) and reconstituted ensiled (from 28% to 35%) corn, total ISDMD increased. With the increase in ISDMD associated with increased moisture also came an increase in degradable intake protein. Likewise, the greatest changes for degradable intake protein occurred in the first 28 days of ensiling. Thus, it would appear that moisture and ensiling may have an impact on ruminal availability of protein. Degree of solubilization of protein also can be impacted by the addition of a microbial inoculant. As mentioned previously, Szasz *et al*. (2005) harvested floury and vitreous high-moisture corn with different kernel moisture contents. A portion of wet corn was rolled and ensiled for 45 days with or without applying a microbial inoculant (Pioneer 1189®). Soluble crude protein was reduced approximately 25% when high-moisture corn was treated with the microbial inoculant, presumably because inoculant dropped pH faster and this reduced the extent of fermentation. Nevertheless, microbial inoculant did not significantly decrease ruminal digestion (data not shown).

Interaction between Endosperm Texture and Kernel Moisture at Harvest

Kernel moisture at harvest also can impact utilization of starch. Correa *et al*. (2002) found that starch vitreousness increased and ruminal fermentability decreased as the kernels matured from one-half milk line to 21 days after the black-layer maturity stage. Additionally, the decrease in ruminal starch fermentability with advancing maturity was greater for grain from a more floury hybrid than it was from a grain from a more vitreous hybrid. This indicates that the difference in starch utilization between floury and vitreous corn hybrids should increase as kernel maturity advances, perhaps due to a crystallizing of starch molecules that may be more pronounced for vitreous compared to floury corn. Nevertheless, the degree to which endosperm texture interacts between kernel maturity levels for high-moisture corn was not understood prior to our investigations. We (Szasz *et al*., 2006) harvested floury and vitreous corn hybrids at 'dry', 'middle', and 'wet' kernel moisture levels (28, 31, and 36.5% kernel moisture at harvest for dry, middle, and wet, respectively). Corn was dry-rolled so that each kernel was fractured into at least two pieces. Following fermentation, the corn was then fed to feedlot steers in a metabolism study. Ruminal, intestinal, and total tract digestibility of starch were equal, and in some cases actually were greater, for high-moisture corn from the vitreous than from the floury hybrid (Figures 2, 3, and 4). Moreover, kernel moisture at harvest was interacted with endosperm texture such that starch digestibility in the rumen and in the total digestive tract of feedlot steers tended to be even greater for the vitreous than the floury hybrid when high-moisture corn was harvested at the driest kernel moisture (i.e., 28% kernel moisture).

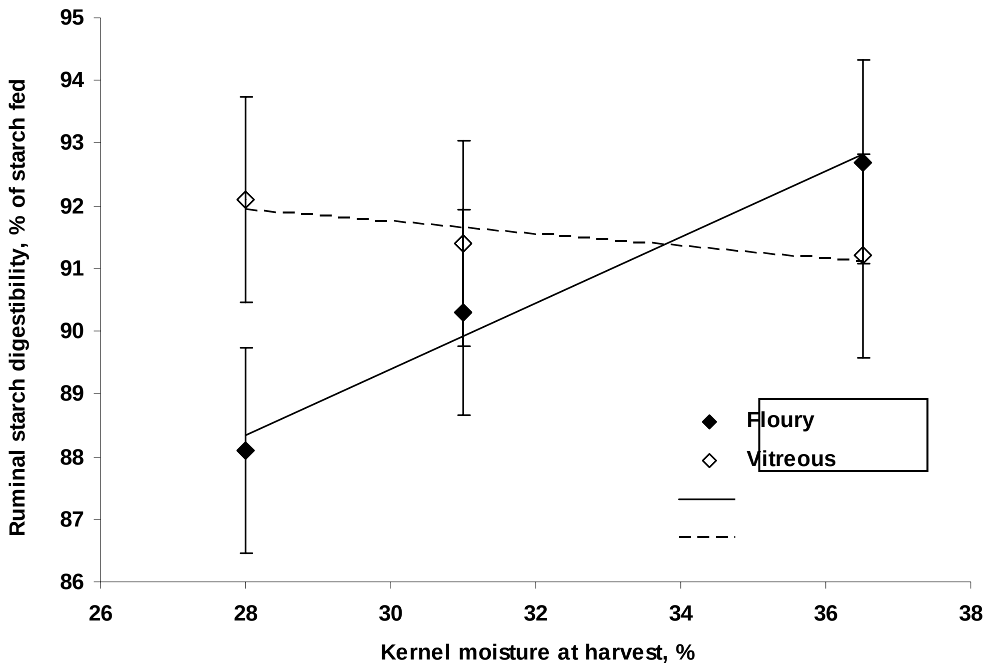

Figure 3. Impact of endosperm texture and kernel moisture at harvest on starch digestion of high-moisture corn in the rumen (Szasz *et al*., 2006). Endosperm type by linear kernel moisture at harvest interaction (P = 0.11).

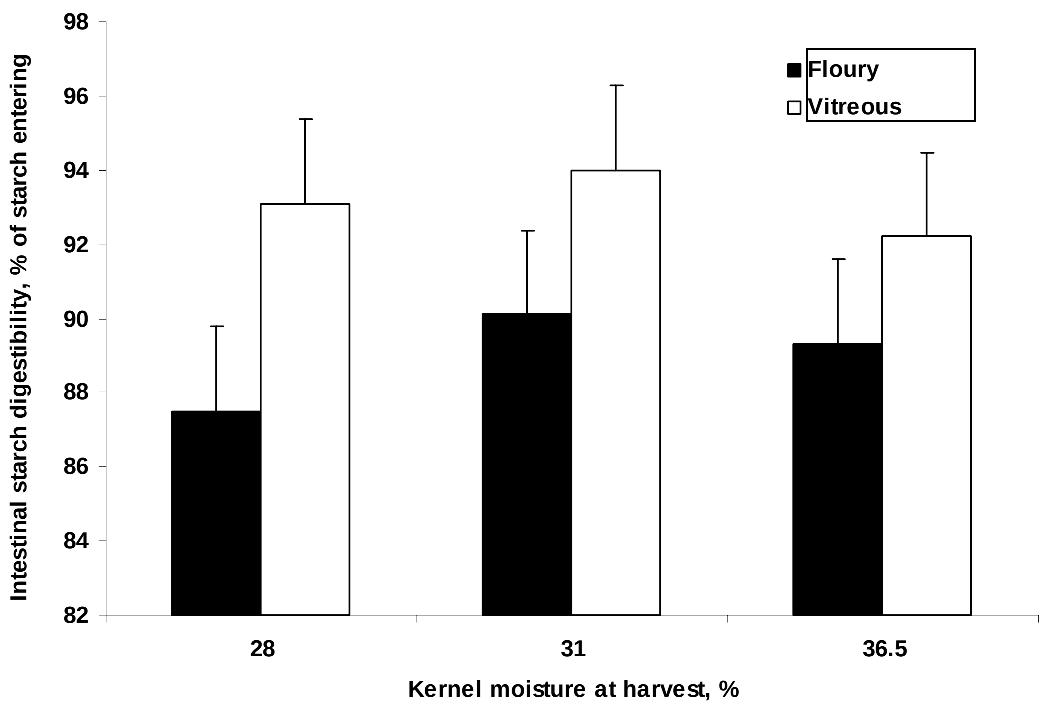

Figure 4. Impact of endosperm texture and kernel moisture at harvest on starch digestion of high-moisture corn in the intestines (Szasz *et al*., 2006). Endosperm type effect (P = 0.02).

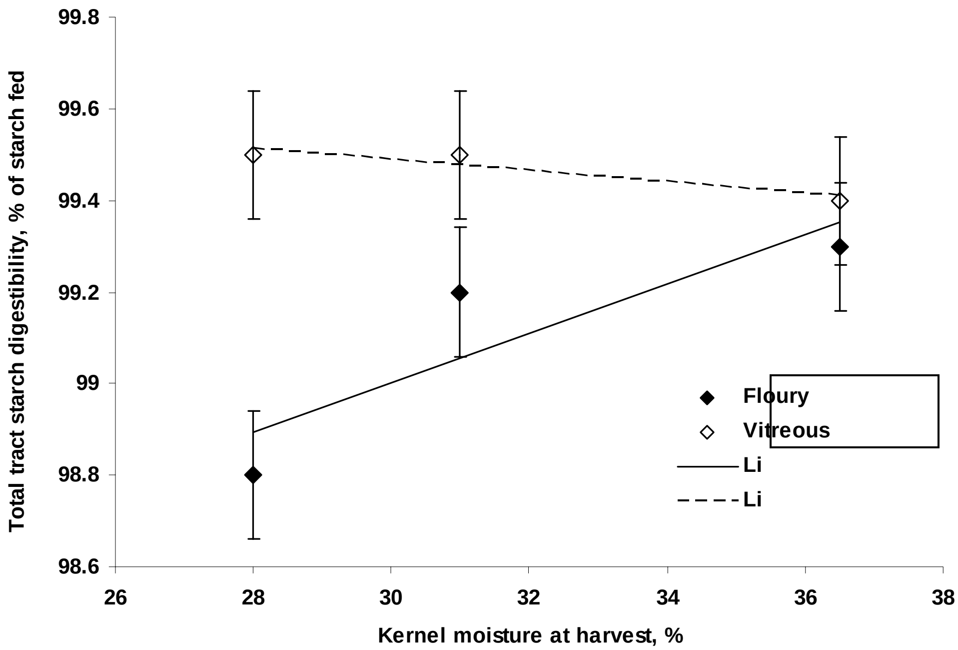

Figure 5. Impact of endosperm texture and kernel moisture at harvest on starch digestion of high-moisture corn in the total tract (Szasz *et al*., 2006). Endosperm type by linear kernel moisture at harvest interaction ($P = 0.09$).

Why should vitreous high-moisture corn have greater starch utilization particularly at a drier kernel moisture level? Fortunately, we measured particle size of the rolled high-moisture corn used in our study. Based on composite samples from six experimental periods, the geometric mean diameter of high-moisture corn fed in our study was smaller for the vitreous than the floury hybrid (Figure 6). Calculated surface area averaged 15.8% more for the vitreous than the floury hybrid (data not shown). These results contrast with those for dry corn where particle size tends to be larger for vitreous corn due to presence of flour released from the floury portion of corn kernels. Presumably, crystallizing of starch molecules with advancing maturity (i.e., beyond black-layer, during kernel dry down) may be more pronounced for vitreous compared to floury corn. Nevertheless, our results suggest that floury corn kernels when moist are pliable and thereby are less damaged by rolling through a mill. In contrast, vitreous corn kernels when moist are more brittle and shatter into finer particles when rolled. Whether these particle size differences can be ascribed fully to vitreousness alone, to the method of comminution, to other genetic or environmental differences among these grain samples that differed vitreousness is not certain. Interestingly, data reported during the 2006 Joint (ASAS/ADSA) Annual Meeting in Minneapolis (Harrelson *et al*., 2006) suggested that corn grain kernels requiring more force to grind were more digestible in the rumen; authors further noted that this response was likely due to a smaller particle size for ground grain derived from the harder kernels. These results correspond with results from studies conducted in our laboratory at the University of Idaho.

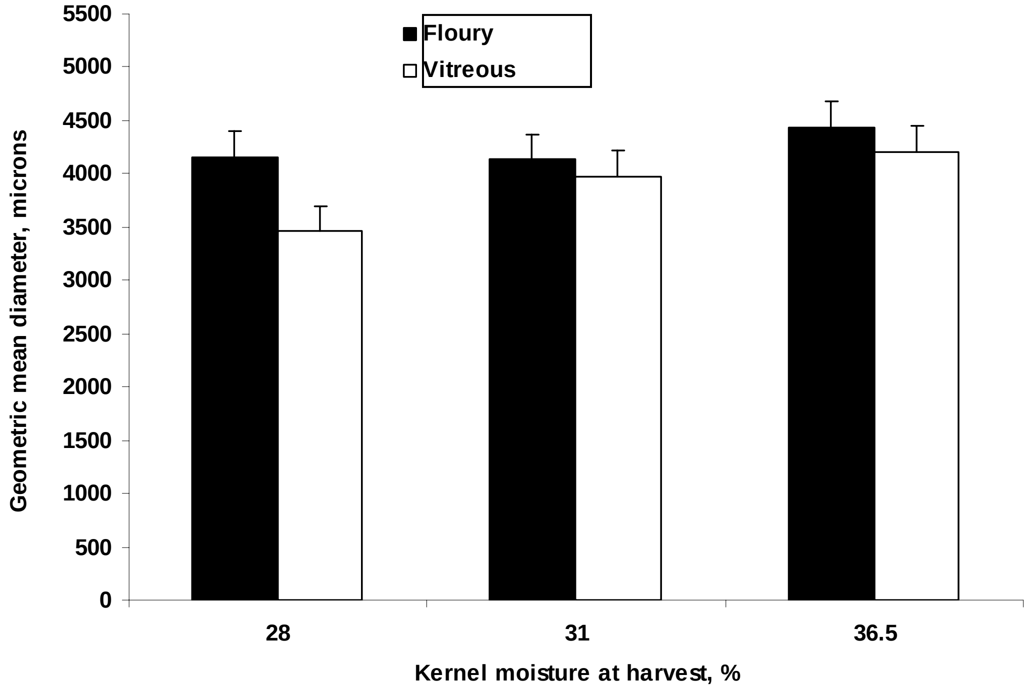

Figure 6. Impact of endosperm texture and kernel moisture at harvest on geometric mean diameter of high-moisture corn (Szasz *et al.*, 2006). Endosperm type effect (P = 0.06).

What is the Optimum Particle Size for High-Moisture Corn?

In our study (Szasz *et al.*, 2006), smaller particle size was surmised as the basis for improved starch utilization associated with vitreous high-moisture corn. Smaller particle size of high-moisture corn from the vitreous hybrid also may be responsible for with the greater total tract organic matter digestibility. In fact, when a quadratic regression model was fitted to our data (Figure 7), the geometric mean diameter of high-moisture corn particles could explain over 96% of the variation in total tract organic matter digestibility. The curvature was due largely to vitreous corn harvested at the driest kernel moisture level (i.e., 28% kernel moisture) as this high-moisture corn treatment produced the greatest total tract organic matter digestibility and the smallest particle size. Although this finding is intriguing, additional data points representing geometric mean diameters from approximately 3500 to 4000 microns are needed to solidify this relationship. Future research might include a test of digestibility of high-moisture corn of different endosperm textures processed to multiple particle sizes. Unfortunately, information on starch digestion in the small intestine was not collected in this study. With total tract starch digestibility for all samples being above 98.8%, a coarser particle size might shift starch digestion from the rumen toward the small intestine. Energetically, starch digested in the small intestine has over 20% greater value than starch fermented in the rumen (Harmon and McLeod, 2001) so that designing diets to decrease the extent of ruminal starch fermentation and increase the supply of starch absorbed from the small intestine may prove advantageous (Channon and Rowe, 2004; Remond *et al.*, 2004).

Only results from further research can reveal the ideal moisture content, particle size, and processing method that will produce the optimum site and extent of starch digestion maximize rate and efficiency of production by growing/finishing beef cattle and of lactation by dairy cows.

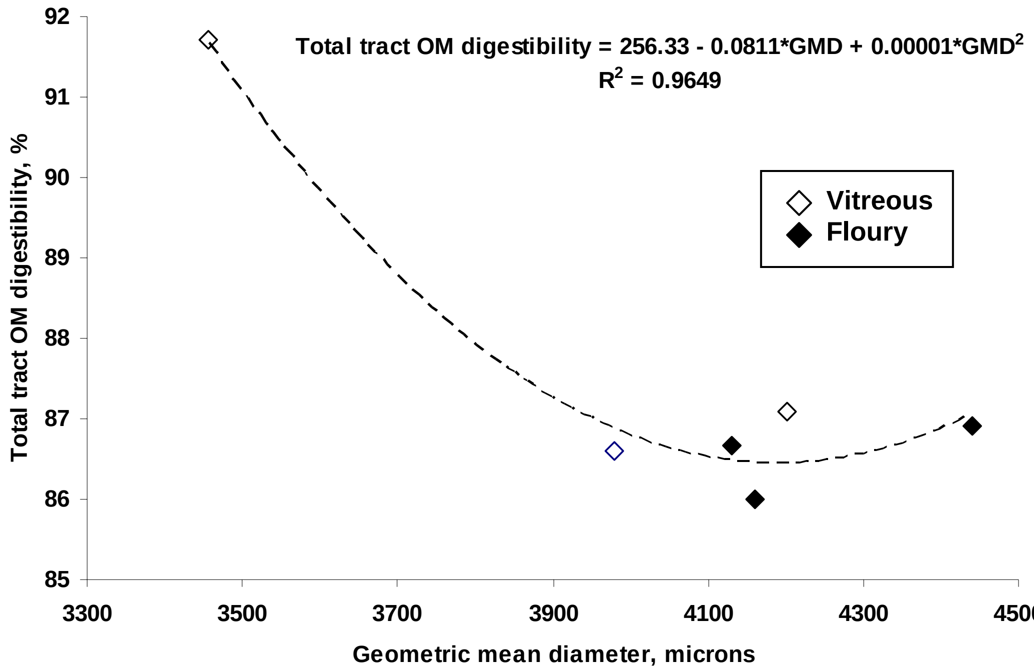

Figure 7. Relationship between geometric mean diameter and total tract organic matter for ensiled high-moisture corn having vitreous or floury endosperm texture (Szasz *et al*., 2006).

Summary and Implications

Potential exists for improving utilization of starch in feedlot and dairy cattle. A multitude of factors can influence utilization of starch from high-moisture corn, but some key factors include starch chemistry (e.g., amylopectin content, crystallization, gelatinization, and retrogradation), starch endosperm type (e.g., degree of vitreousness), non-starch constituents (i.e., protein matrix), and kernel moisture content. Circumventing many of the negative effects associated with these factors is made possible through reducing particle size during kernel processing. Optimum particle size for high-moisture corn is not well defined however. This is a difficult task though because of the interactions which sometimes exist between comminution, kernel moisture, and corn hybrid. Nevertheless, research is needed to identify ideal moisture content(s), particle size(s), and processing method(s) that strikes a balance between economic, agronomic, animal performance, and animal health considerations.

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