CORN PARTICLE SIZE FOR FEEDLOT CATTLE: EFFECTS ON PERFORMANCE, CARCASS TRAITS AND RUMINAL FERMENTATION

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Format of Dissertation

This dissertation is presented in the Journal of Animal Science style format, as outlined by the Oklahoma State University graduate college style manual. The use of this format allows for independent chapters to be suitable for submission to scientific journals. Three papers have been prepared from the data collected for research to partly fulfill the requirements for the Ph.D. degree. Each paper is complete in itself with an abstract, introduction, materials and methods, results and discussion, implications and literature cited section.

CHAPTER I

GENERAL INTRODUCTION

High concentrate diets have been fed to beef cattle in the United States for over two hundred of years. Large scale, confined cattle feeding operations developed in the late nineteenth century when cottonseed oil mills in OK and TX disposed of their wastes (cottonseed hulls and meal) by feeding them to cattle. Currently, nearly one million head of fat cattle are marketed annually coming from over 200 OK feedlots. The staple diet today for the majority of these cattle is corn. Corn processing began in the mid-nineteenth century when hammer milling of grain was reported to improve feed conversion. Steers fed then were two to three years of age and grain processing greatly improved its utilization. Steam-flaking was introduced in the late 1940's as a method to increase grain utilization further; it still is used widely.

The primary goal of processing is to increase grain (starch) digestibility. This is accomplished by increasing the surface area for attack by microbial or intestinal enzymes. Increasing the extent of ruminal digestion decreases the amount of residual starch to flow to the small intestine. Maximizing ruminal fermentation of grains generally increases digestibility of starch in the total digestive tract. However, digestion of starch by mammalian enzymes in the small intestine rather than fermenting starch in the rumen avoids certain losses associated with ruminal fermentation, i.e., heat and gas (methane). A proper balance between ruminal and small intestinal starch digestion should increase the total quantity of energy available for use by the animal. Although shifting starch digestion post-ruminally may lower total tract digestibility of starch, such a shift may increase energy retention by the animal. Site of digestion depends on several factors including dietary roughage level and type, grain particle size, animal age, feed intake, and interactions among these factors.

The objective of this research was to characterize how processing alters the size and distribution of grain particles from processed grain, and examine how these measurements alter performance of feedlot cattle. For this research, we used both dry corn in the dry rolled and dry whole form and high moisture corn that had been rolled or ground. When combined with data from other experiments, this information should help to tune grain processing more precisely so as to optimize energy use by feedlot cattle thereby reduce cost of producing high quality beef.

CHAPTER II

LITERATURE REVIEW

Introduction: Digestion

Starch is the chief component of high concentrate feedlot diets. Cattle typically are fed diets containing 80 to 95% grain and grains contain 70 to 75% starch. Obviously, efficient utilization of starch by feedlot cattle is of utmost economic importance to cattle feeders.

Starch is a glucose polymer composed of two major types of molecules: amylose and amylopectin. Amylose is a linear polymer of α-1,4-linked D-glucose units. Amylopectin, the most abundant (70 to 80%) component of normal starches (French, 1973), is a much larger, branched polymer composed of linear chains of α-1,4-linked D-glucose with α-1,6 branch points every 20 to 25 glucose molecules.

Starches exist in highly organized granules in which amylose and amylopectin are held together by hydrogen bonding. These granules range in size from submicron to more than 200 μm in diameter. These granules are arranged in a crystalline structure inside the endosperm; in corn and milo grains, starch granules are held together either loosely in the "soft starch" portion or buried in a protein matrix which resists enzyme and microbial attack in the "horny endosperm." Undamaged starch of the horny endosperm has low susceptibility to enzymatic attack and, therefore, incomplete digestion (Rooney and Pflugfelder, 1986). McNeil et al. (1975) suggested that the primary effect of processing was upon the solubility (or integrity) of the protein matrix which either encapsulate or bind starch granules together.

To be digested, starch must be exposed for attack by enzymes (both microbial and mammalian). Processing of cereal grains, either mechanically prior to feeding or by chewing and rumination by the animal, increases the exposure of starch for enzymatic attack and digestion (Hale, 1973; Waldo, 1973; Nordin and Campling, 1976; Ørskov, 1976; Galyean, 1977; Teeter et al., 1980; Ørskov, 1986; Theurer, 1986; Anzola, 1987). Grain currently is fed to cattle in various forms, the primary forms being whole (unprocessed), rolled, ground, high moisture (ensiled) and steam-flaked or steam-rolled. Though vastly different in their approach, each of these forms of grain processing or storage increase the surface area which is exposed for microbial attack and increase starch solubility in the rumen. Hence, energy availability to the animal is increased.

Surface area increases exponentially as particle size is reduced (Ensor et al., 1970). Particle size (or surface area) thereby are important factors affecting the site and extent of starch digestion (Waldo, 1973). Indeed, the site of starch digestion may be as important or more important than the extent of digestion. Starch digestion in the small intestine theoretically is more energetically efficient than ruminal digestion because both methane and heat loss are reduced and absorbed products may be beneficial energetically (Owens et al., 1986). However, increasing the flow of starch to the small intestine may reduce total tract digestibility and depress energy utilization (Theurer, 1986). Based on regressions, Hale (1973) and Theurer et al. (1986) both concluded that animal performance is correlated with total tract starch digestion which in turn generally is correlated with extent of ruminal starch digestion. This review will discuss the role of grain (corn and milo) particle size on site and extent of digestion of starch and effects on performance of feedlot cattle.

Starch Digestion in the Small Intestine

Depending on processing method, up to 40% of corn starch may escape fermentation in the rumen (Ørskov, 1986). Although only 10 to 25% of the starch in steam-flaked corn escapes digestion in the rumen, some 30 to 45% of the starch in dry rolled corn escapes ruminal fermentation and flows to the small intestine (Theurer, 1986). Averaged across processing methods, small intestinal digestibility of starch was 52.9 ± 18.6% (Owens et al., 1986). This value indicates that the usefulness of starch that escapes the rumen is relatively low and quite variable. This variability may be due to differences in size of the particles escaping ruminal digestion, pH of digesta, quantity of pancreatic amylase, speed of passage, and level of feed intake. One might expect digestion of residual starch to be lower than digestion of dietary starch; this is because the smaller, more readily digested particles already should have been fermented by microbes in the rumen.

Supply of starch for digestion in the small intestine typically is greater when dietary corn has a larger particle size. However, larger particles are digested less extensively in the small intestine than smaller particles (Galyean et al., 1979; Anzola, 1987). Non-starch components such as the protein matrix which binds starch granules together and presence of tannin and thick seed coat, which shelters hard starch from digestion, limit attack by both microbes and enzymes. Starch that reaches the duodenum in large particles is poorly digested in either the small or large intestine (Owens et al., 1986). Generally, the more extensively processed grains are more extensively digested in the small intestine, so processing appears to increase extent of digestion both in the rumen and in the small intestine (Owens et al., 1986).

Ruminal pH and duodenal pH have been suggested to alter small intestinal starch digestibility. Wheeler and Noller (1977) observed that the amount of starch in feces declined when pH in the small intestine fell. High intakes of concentrate diets were associated with a lower intestinal pH, presumably due to increased acidity of the ingesta entering the small intestine (Wheeler and Noller, 1976). When ruminal pH is below 6.9, activity of pancreatic amylase is reduced which in turn may decrease rate of digestion of starch in the small intestine. This led to the suggestion that incomplete digestion in the small intestine may be due to inadequate amylolytic activity in the small intestine. In a series of performance trials, Brink et al. (1984) found that supplemented limestone increased ruminal pH, tended to improve feed:gain ratio, and decreased fecal starch. However, Rust (1983) found that ruminal pH and fiber digestion were increased by added limestone, but starch digestion was not affected by the addition of limestone to high concentrate diets. Further, Zinn et al. (1982) studied duodenal and ileal pH of intestinally cannulated steers fed various diets and several concentrations of limestone. They detected no effects of either diet or limestone on intestinal pH contradicting the findings of Wheeler and Noller (1976) which were based on samples of digesta from the small intestine obtained after steers had been slaughtered and eviscerated. Perhaps the peristaltic rush during the stress of slaughter pushed abomasal contents into the small intestine and led Wheeler and Noller (1976) to erroneous conclusions.

Pancreatic enzymes cannot digest unlimited quantities of starch in the small intestine (∅rskov, 1986). Little et al. (1968) introduced slugs of starch in the abomasum of steers. At lower infusion doses, the majority (59.9%) of starch disappeared in the small intestine and very little (6.5%) was found in feces. But as the pulse dose of starch increased, the percentage disappearing in the small intestine decreased and the percentage found in the feces increased. Although significant quantities of starch disappeared from the small intestine, the blood glucose concentration was not increased. These authors concluded that digestion of starch by pancreatic enzymes in the intestine may be inadequate for optimum utilization. Larsen et al. (1956) found that starch introduced into the abomasum was not hydrolyzed and utilized in the small intestine. Although blood glucose levels were increased when glucose or maltose was placed in the abomasum, they were not increased by starch. Similar results were obtained by Kreikemeier et al. (1991) where only about 35% of the raw corn starch disappearing in the small intestine appeared in the portal vein as glucose.

Metabolizable energy (ME) intake also may alter the extent of digestion of starch in the small intestine. Russell et al. (1981) found that fecal starch of steers fed cracked corn diets increased from 11 to 31% as the level of ME intake increased from one to three times maintenance, yet the total amount of starch digested in the small intestine tended to increase as starch concentration in the diet increased. Nevertheless, small intestinal starch digestion as a percentage of starch intake remained relatively constant as the level of starch in the diet increased. Because the quantity of starch absorbed continues to increase as supply of starch increases, an absolute limit on the amount of starch digested may not be attained under practical conditions. Digesta spends less than 3 hours in the small intestine (Owens et al., 1986). Perhaps the extent of digestion would be increased if residence time in the small intestine were increased.

What limits starch disappearance in the small intestine is not known and might differ under different conditions. Generally, by increasing the total amount of energy available to the animal, increasing starch digestion in either the rumen or small intestine improves efficiency of energy utilization and the feed:gain ratio. Grains which are extensively degraded in the rumen generally have the highest overall starch digestibilities (Ørskov., 1986). However, starch fermented in the rumen is used only 70% as efficiently as starch digested in the small intestine for gain by steers (Waldo, 1973). Based on regression of gain:feed ratio against ruminal and small intestinal starch digestion, starch digested in the small intestine provides 42% more energy than starch digested in the rumen (Owens et al., 1986) which again indicates that ruminal fermentation is 70% as efficient as small intestinal digestion. Although maximum starch digestibility should maximize feed efficiency (gain/feed ratio), an optimum balance between ruminal and small intestinal digestion of starch may maximize energetic efficiency. Table 1 outlines the relative advantages and disadvantages of starch digestion in the rumen and small intestine.

Effects of Rolling or Grinding Corn or Milo

Rolling or grinding of corn and milo has been practiced for many years to increase availability of energy from grain. The extent to which processing is necessary for various grains differs widely. Because whole milo produces unacceptably poor feed efficiency, it is not used widely (Owens et al., 1995). However, whole corn is well utilized in feedlot diets and often serves as the standard when comparing processing methods.

Fine grinding or rolling of grain generally increases total tract DM disappearance. In vitro studies have shown that DM disappearance in the rumen and the total tract increases as particle size decreases for both corn (Walker et al., 1973) and milo (Berry and Riggs, 1971). Wilson et al. (1973) showed that rate of disappearance in situ was faster for coarsely ground than whole grain. Although whole corn kernels resist digestion, when corn kernels were cut in half, the hollow seed coat was all that remained after 48 hours of ruminal incubation. This illustrates how the seed coat protects seed contents from digestion. Fine grinding is necessary to maximize the extent of digestion (Anzola et al., 1988; Ohh et al., 1993).

Whole corn can be well utilized by feedlot cattle. Murphy et al. (1994) fed whole or rolled corn to rumen fistulated steers (400 kg). Organic matter digestibility was 4% lower for the rolled corn than the whole corn (81.4 vs 84.7%) even though starch digestion was slightly greater for rolled corn (97 vs 96%). Typically, more fines and dust are present in rolled corn than in whole corn diets. Undesirable factors associated with fine grinding or rolling, such as fines and dust, may decrease feed intake and increase the potential for acidosis. Ruminal volumes of steers tend to be higher when they are fed whole rather than rolled corn. With ad libitum feeding, rolling the corn reduced the acetate and increased the propionate proportion in the rumen. Proportion of ruminal butyrate also tended to be greater with rolled (12.9%) than whole corn (11.0%) and rolled corn produced higher total VFA concentrations in ruminal liquor at 3, 4, 6, and 9 h post-feeding. Greater VFA concentrations at these times may reflect more rapid fermentation of rolled than whole corn. However, because ruminal volume is greater for steers fed whole corn, the higher VFA concentration may be due simply to greater dilution of ruminal contents with digesta and saliva in steers fed whole corn. Twelve hours after feeding, no effects of corn processing on ruminal VFA concentrations were evident. At 2, 3, 4, 6 and 9 hours after feeding, ruminal pH was lower for steers fed rolled corn than those fed whole corn. However, at 24 h after a meal, steers receiving whole corn had lower ruminal pH (5.95) than steers fed rolled corn (6.26). Such differences may be irrelevant for feedlot cattle that nibble throughout the day rather than consume one single large meal each day.

Similar results were obtained by Goetsch et al. (1986) with steers fed ground or whole corn diets. Ruminal pH at 2 and 6 hours post-feeding was lower for steers fed ground corn diets. However, ruminal and total tract OM and starch digestibilities tended to be higher with ground corn diets. Higher ruminal pH values in both studies reflect either slower fermentation of or a greater ruminal dilution rate with whole corn diets.

Shuey et al. (1994) fed corn whole or dry rolled with either 0 or 8% chopped alfalfa hay. Roughage level and grain processing had no effect on the molar percentage of acetate or total VFA concentration in the rumen. Ruminal pH at 3 hours post-feeding was lower for the zero roughage diets. Ruminal pH at both 3 and 6 hours post-feeding was lower while lactate concentrations were higher for steers fed rolled corn than those fed whole corn. Adding roughage or feeding whole corn decreased the amount of time pH remained below 5.2 and thereby might reduce the opportunity for subacute acidosis.

Sharp et al. (1982) fed steers ground or whole corn with 10% roughage. Liquid turnover rate was 29% higher with steers fed whole corn. Greater liquid turnover presumably reflects greater saliva input. Ruminal pH and total concentrations of VFA were not altered by form of grain, probably due to frequent (hourly) feeding. Relative VFA concentrations were altered by grain form; propionate was less while acetate and butyrate were greater with whole than ground grain. Total production of VFA, measured with isotopes, totaled 60 and 48% of the consumed energy for the whole and ground corn diets respectively. This indicates that ruminal digestion of the whole corn diet actually exceeded that of the ground corn diet. Chewing and rumination and limited feed intake may have enhanced the extent of ruminal digestion of whole corn.

Mastication and Rumination: Factors in Digestion

Chewing and ruminating can influence the utilization of whole corn diets (Teeter et al., 1980; Ewing et al., 1986). Undamaged corn kernels remain virtually inert in the ruminant digestive tract (Galyean, 1977; Anzola, 1987). Hence, chewing is of utmost importance for the utilization of whole corn. During consumption, only whole corn (as opposed to processed corn) is detectably reduced in particle size by chewing (Ewing and Johnson, 1987).

Nicholson et al. (1971) demonstrated that animal age may alter the need for grain processing. The DM digestibility of whole barley fed to mature cows was increased from 63.4 to 83.4 % by grinding. In contrast, DM digestibility of whole barley was increased much less (from 72.2 to 79.0%) in calves by grinding.

Wilson et al. (1973) found that when whole corn was fed to mature cows, individual animals had apparent digestibilities that varied greatly. Digestibility was related inversely to the amount of whole kernels present in the feces reflecting differences in mastication of the grain. Less variation in digestibility was noted when grain was ground prior to feeding it to cows supporting the concept that inadequate chewing and rumination are responsible for low digestibility of whole corn. Cows with higher digestibility values chewed and ruminated more than cows with lower digestibilities.

Higher total tract digestibilities for grains are noted with sheep than with cattle; this also may be due to more extensive chewing by sheep. With sheep, processing whole grains resulted in only small increases in total and ruminal starch utilization (Theurer, 1986). The average percentage of starch escaping ruminal fermentation in sheep is markedly lower than for cattle (11 vs up to 43%).

Beauchemin et al. (1994) stated that mastication alters the kinetics of ruminal digestion of unprocessed cereal grain. Whole corn was substantially damaged after ingestive mastication, and the majority of kernels were broken into small pieces. Corn kernels are extensively damaged during ingestive mastication, reducing the need for physical processing.

Cattle age and roughage level in the diet affect the extent of mastication. Younger cattle chew feed more thoroughly than do older cattle (DeBoever et al., 1990). As cattle get older more feed is consumed in a shorter period of time (Chase et al., 1976). Mader et al. (1990) found that the addition of 10% roughage to whole corn diets decreased the amount of whole corn in the masticate by 44% (9.7 vs 17.3%). Moisture level of the corn did not affect the percentage of whole corn remaining in the masticate. Geometric mean diameter of corn found in the masticate that was fed whole (with 10% roughage) was 3,893 μm. This compares with whole corn kernels at approximately 6,000 μm.

Animal performance may be affected by rumination. Owens and Ferrel (1983) observed the behavior of steers fed whole corn diets. Steers observed to be ruminating more frequently had greater ADG while those that made more visits to the feedbunk ruminated less. These studies illustrate the importance of chewing and rumination with whole corn diets. In general, young cattle digest starch nearly as well when fed whole corn as when fed rolled or ground corn.

Comparisons of Steam-Flaked, High Moisture and Dry Grains

Gelatinization (steam-flaking) and moisture level (high moisture ensiling and steam-flaking) of grain affect digestion by increasing the surface area of the grain and its solubility in the rumen (Theurer, 1986). Steam-flaked grain is prepared by heating grain with steam prior to rolling to produce a thin flake. The degree of flaking (as measured by thickness of the flake) is the principal factor that improves availability of starch to enzymatic degradation (Osman et al., 1970). High moisture corn is harvested early while moisture level is approximately 30%. After harvest, the grain typically is ground or rolled prior to ensiling. More extensive processing methods (flaking, early harvest, reconstitution) generally increase ruminal and total tract digestibility of the diet and improve feed efficiency (Hale, 1984).

Zinn et al. (1995) fed 208 kg Holstein steers dry rolled or steam flaked corn at 2 different intake levels. The diet consisted of 88% concentrate and 12% roughage. Steam flaking increased ruminal digestibility of OM (56.5 vs 65.5%) and starch (70.6 vs 85.4%). When sampled four hours post-prandially, molar proportion of acetate and pH were lower while molar proportion of propionate was greater with the steam-flaked corn. Post-ruminal OM and starch digestion, calculated as a percentage of intake, tended to be highest with the dry-rolled corn diet. However, total tract digestibilities of OM (76.6 vs 83.0%) and starch (89.8 vs 99.1%) were increased by steam-flaking.

Similar results were obtained by Galyean et al. (1976) who fed an 85% concentrate 15% cottonseed hull diet. Dry rolled, steam flaked and ground high moisture corn were compared in a digestion trial. Ruminal starch digestibilities were 89.3, 82.9 and 77.7% for ground high moisture, steam flaked and dry rolled corn respectively. No differences were detected in intestinal starch digestibility. Total tract starch digestibilities were higher for ground high moisture and steam flaked than dry rolled corn (99.1 and 99.1 vs 96.3%). Ruminal pH was lower and VFA concentration greater 2 and 4 hours post-feeding for ground high moisture followed by steam flaked and dry rolled corn. In vitro ruminal DM disappearance was greatest after 3, 6, 9 and 12 hours for the ground high moisture corn. Hibberd et al. (1983) showed that reconstituted (water added to dry grain and stored under anaerobic conditions) milo had higher starch digestibilities in the rumen, the small intestine, and the total digestive tract than dry rolled grain sorghum.

Johnson et al. (1968) measured rates of ruminal digestion and passage in steers. Compared with cracked corn, steam flaked corn had a 9 hour faster rate of passage and 4 to 6% greater DM digestibility. Although less energy was lost as methane gas from steam flaked corn, no difference in VFA ratio in the rumen was detected. Fiems et al. (1990) measured in situ disappearance on ground, rolled or steam-flaked corn. After 48 hours, no difference was detected in DM disappearance. This indicates that when the grain spends long enough in the rumen, these methods of corn processing had no effect on DM disappearance although if the corn were present as whole kernels, it would remain largely undigested.

In an extensive digestion trial, Ramirez et al. (1985) confirmed that starch digestibility was higher for steam flaked (99.1%) than for whole steamed (93.8%) and whole corn (93.0%). Retention time in the rumen was highest for whole corn followed by whole steamed and steam flaked corn. Undoubtedly, steam flaking increases digestibility of corn and subsequent efficiency of feed use. However, this data suggests that steaming alone is inadequate; in order to increase digestion and animal performance, the steaming process must be followed by rolling or flaking to increase the surface area of grain. An alternative explanation for this observation is that starch in grain that is not cooled rapidly after flaking will retrograde to an indigestible form.

Aguirre et al. (1984) fed corn as whole, rolled, or steam-flaked grain to heifers. Digestibility of starch entering the rumen, the small intestine and the large intestine all were increased by more extensive grain processing. Fecal starch decreased as the degree of processing increased. This supports the concept that particle size or surface exposure limits ruminal and intestinal digestion of starch.

Compared with corn that is dry rolled or ground, steam flaked and high moisture corn are more extensively digested both in the rumen and in the total digestive tract of feedlot cattle. Processing typically decreases ruminal pH but increases passage rate and total VFA concentration in the rumen. If extent of ruminal starch digestion is increased, less remains to be presented to the intestines for digestion there. Regardless, the intestinal digestibility of the residual starch typically is increased by processing, too. Nevertheless, the amount of starch digested post-ruminally by cattle is markedly less for highly processed grain than whole grain. This means that grain processing generally shifts the site of starch digestion from the intestines back toward the rumen.

Particle Size Effects on Digestion

Grain particle size has been quantified by sieving procedures in several digestion trials. These trials generally have used dry corn that has been rolled or ground.

In early studies with lactating dairy cows, milo was ground to produce three different mean particle size (fine = 315 μm; medium = 584 μm; coarse = 641 μm). Total tract starch digestibility, total ruminal VFA concentration, and milk production all increased as particle size was decreased. The particle sizes used in this study were much finer and roughage levels were much higher than would be used in a feedlot diet. However, results of this study demonstrate that starch digestion and performance can be enhanced by decreasing to particle size to a very fine powder.

Nordin and Campling (1976) found that only 24% of whole corn grain DM was lost after being suspended in the rumen for 72 hours. When corn kernels were broken in half, 42% of DM was lost after 48 hours. Further processing showed that finely ground corn (median particle size, 2,500 μm) disappeared faster than coarse (median particle size, 3,600 μm) at 12 (22 vs 12%), 24, 36, 48, and 60 hours.

Galyean et al. (1981) sieved dry ground corn to obtain 4 distinct particle sizes (6,000, 3,000, 1,500, and 750 μm); these were incubated in situ for 2, 4, 6, or 8 hours. Very little loss of DM or starch occurred with the larger particle sizes (6,000 and 3,000 μm). However, DM and starch disappearance increased markedly as particle size decreased. High moisture corn was sieved in the same manner as described above. High moisture corn particles exhibited a linear increase in DM and starch disappearance as particle size was decreased. Ruminal loss of starch and DM were greater for high moisture than for dry corn as would be expected due to the higher solubility of high moisture corn. Similar results were attained by Cerneau and Michalet-Doreau (1991) where three fractions (approx. 800, 3,000 and 6,000 μm) of sieved corn were evaluated in situ. One difficulty with these sieving studies is that the particle of different sizes may differ in chemical or physical composition and not parallel effects if all the grain were ground to a specific particle size.

Thomas et al. (1988) prepared two fractions (approx. 5,000 and 1,500 μm) of cracked corn particles by sieving procedures and measured disappearance in situ. Although the 1,500 μm corn disappeared faster (9%/h) numerically than 5,000 μm corn, this difference was not significant.

McAllister et al. (1993) collected two fractions (approx. 570 and 2,500 μm) of barley and corn for an in vitro digestion study. For both grains, extent of digestion of starch from the small particles was greater than from the large particles. Factors in addition to particle size also may be important; treatment of grain particles with proteases has increased starch digestibility. Examination by scanning electron microscopy revealed that grinding broke endosperm cells open but that starch granules still remained embedded within a protein matrix.

Galyean et al. (1979) conducted a study in vivo; they fed corn whole (5978 μm) or ground to 3 different mean particles sizes (509, 588 or 832 μm) in 80% concentrate diets. Steers were fed eight times daily at 3 hour intervals. Ruminal DM digestibility was lower for whole corn than for ground corn but post-ruminal DM digestibility was highest for whole corn; this reflects the quantitative importance of intestinal digestion of whole corn. Ruminal starch digestion increased as particle size was decreased. Total tract starch digestion was lower for whole corn (88.2%) than for all of the ground treatments (average 93.9%). Although ruminal pH was similar for all treatments, it tended to decrease as particle size decreased. This is similar to pH changes noted by Hironaka et al. (1979). Rumen outflow rate tended to decrease as particle size decreased. These data suggest that larger corn particles are not held in the rumen any longer than smaller particles and may, in fact, pass more rapidly. However, release of markers from fermented grain particles may complicate interpretation of data related to rate of passage. Molar percentages of VFA and total VFA concentration were not influenced by corn particle size. Data from this study suggest that decreasing corn particle size in the diet from 823 to 509 μm geometric mean diameter had little effect on ruminal, total and intestinal DM, OM and starch digestion. However, the larger the particle size, the greater the shift in site of digestion from the rumen to intestines and the greater the potential for digestibility to decrease. This work is a agreement with earlier work by Galyean et al. (1981) and demonstrates how reducing the particle size below 1,500 μm can increase digestibilities of DM and starch.

Turnbull and Thomas (1987) sieved dry cracked corn (similar to Galyean, 1977) to obtain particles sizes on 1,000, 2,000 and 4,000 μm which were mixed into diets containing 30% cottonseed hulls. The length of time required for mixing various corn particles in the rumen did not differ. The 1,000 and 2,000 μm particles appeared to leave the rumen an average of 14% faster than the 4,000 μm particles, though these differences were not significant statistically. Similarly, Ewing et al. (1986) found that reducing corn particle size from 6,000 to 1,000 μm accelerated ruminal passage rate of tagged corn particles. In contrast to Galyean et al. (1979), these trials indicate that smaller particles (1,000 to 2,000 μm) actually may flow more rapidly to the small intestine and, by virtue of their smaller size, be more highly digested at that point. The frequent feeding interval used in Galyean et al. (1979) may affected the outflow of particles.

Burghardi et al. (1990) fed rolled (2,400 μm) and whole (6,000 μm) corn to ruminally, duodenally and ileally cannulated steers. Total tract OM digestion tended to be greater with rolled corn. Ruminal OM digestion was increased by processing. Ruminal digestion of starch was increased by processing (70.0 vs 56.5). However, cattle fed whole corn digested a larger proportion of dietary starch in the small intestine than those fed cracked corn (25.1 vs 18.6).

Lall et al. (1984) fed mature cannulated Jersey crossbred steers three particle sizes; these included broken (approx. 3,500 μm), coarse (approx. 2,235), and powder (approx. 900 μm). Total tract and ruminal DM digestibility increased as particle size decreased. In situ work by Teeter et al. (1980) produced similar results with whole, scratched, coarsely ground (5,000 µm) and medium ground (2,500 µm) corn

Anzola (1987) studied the disappearance of corn particles ranging from <125 to 2,000 µm using a unique mobile dacron bag technique. Rolling corn (2,785 µm) increased the extent of starch disappearance at all sites (rumen, small intestine and total tract) when compared with whole corn (4,758 µm). Some (7.4%) disappearance of starch occurred with the whole corn kernels placed into the small intestine, however, no starch was lost from whole corn placed in the rumen for 15 hr. The quantity of starch and protein disappearing in the small intestine and rumen (% of supply) increased as particle size was reduced. Extent of DM disappearance in the rumen increased linearly as particle size was reduced. Ruminal or abomasal digestion increased susceptibility of particles to intestinal digestion, perhaps by removing some barriers to digestion (partial degradation of the protein matrix). Smaller particles disappeared to a greater extent than large particles at all sites (rumen, small intestine and total tract).

Turgeon et al. (1983) used ruminally cannulated steers (351 kg) to determine digestion coefficients for whole (5,977 µm), cracked (2,384 µm) and a mixture of whole plus cracked (average 4,181 µm)corn diets. Total tract DM and OM digestion were not different among treatments. Extent of ruminal and post-ruminal digestion also was not affected significantly by particle size although more starch tended to digested in the rumen for the cracked corn diet. However, more starch was present in the feces of steers fed whole corn. Consequently, total tract starch digestion tended to be greater for the cracked diet than the whole corn diet. The author suggested that about half of the starch fed in the whole corn diet was subjected to post-ruminal digestion. The mixture (whole plus cracked corn diet) produced starch digestibilities and fecal starch contents intermediate to the other two. They speculated that the mixture of cracked and whole corn should slow ruminal fermentation and provide starch for intestinal digestion yet provide a relatively high level of total tract starch digestibility. They suggested that both the mean size and the distribution in size of particles may help to balance ruminal and intestinal digestion in order to optimize the efficiency of energy usage. This was tested later in feeding trials.

Associative Effects of Grains and Processing Methods

Many cattle in commercial feedlots are fed mixtures of grains or a single grain processed by several different methods. Feeding a mixture of grains or a single grain processed in by several different methods may increase feed efficiency, but whether this is due to improved bunk and feeding management and increased energy intake or some metabolic advantage in energy availability of the total diet is not clear. Some researchers have proposed that a proper mixture may optimize the rate of fermentation while balancing ruminal and intestinal digestion of starch. Certainly, by diluting an acidotic grain like wheat with anything that is less readily fermented may improve performance by decreasing the incidence of metabolic problems. The proof for an advantage of a mixture, like for an associative effect, depends on detecting a statistically significant departure from linearity for the mixture.

Streeter et al. (1989) fed 315 kg cannulated heifers in a 5X5 Latin square. High moisture milo and(or) dry rolled corn. The grain portion of the 92% concentrate diet consisted of ratios (high moisture milo:dry rolled corn) of 0:100, 25:75, 50:50, 75:25 and 100:0. Digestibilities of OM in the total tract declined linearly as high moisture milo replaced dry rolled corn . A quadratic response in extent of starch disappearance in the rumen was noted; blends were lower than either individual grain. Extent of starch digestion in the rumen averaged 82.7% compared with only 2.9% in the small intestine and 5.7% in the large intestine. Altering the ratio on high moisture milo to dry rolled corn had more effect on ruminal fermentation than on digestion in the small intestine.

Mendoza et al. (1991) indicated than intake of starch and DM and in situ rate of starch disappearance of dry rolled milo increased as milo was added to a high moisture corn diet. However, in situ disappearance of high moisture corn was not affected. When steers were fed a mixture of the grains, activities of protozoa and amylase tended to be higher whereas lactate concentration tended to be reduced. Ruminal pH was not affected. Improvements in feed efficiency observed with feeding grain mixtures may be related to changes in protozoal populations and amylolytic enzyme activities.

Lee et al. (1982) found than OM and starch digestion both in the rumen and total tract increased as the level of steam flaked corn increased in the steam flaked-dry rolled corn diet. Ruminal pH and acetate:propionate ratio decreased as the level of steam-flaked corn increased. However, Stock et al. (1987) found an increased ruminal and total tract starch digestion for diets that contained a combination of high moisture corn and dry rolled milo rather than either grain alone. Thus, they attributed a portion of the complementary effect of grain mixtures to an increase in starch digestibility.

Results from the limited research in this area are inconclusive. Numerous combinations of grains and processing methods are possible and have not been well studied. The effects of mixing two grains or processes together may be similar to that of increasing the distribution of particles and may be studied most practically by examining results of animal performance trials.

Introduction: Performance

The primary goal of grain processing is to increase starch availability to the animal and thereby improve efficiency of feed utilization. As discussed earlier, the site and extent of starch digestion is affected by grain processing method, moisture level and particle size (surface area) of the grain. Presumably, maximum digestion of the grain will lead to the most efficient feedlot gains (Theurer, et al., 1986). However, the proper balance of starch digestion in the rumen and small intestine might lower overall starch digestion but improve feed efficiency (Owens et al., 1986). Animal performance is ultimately the best parameter to gauge the effectiveness of corn processing and particle size. The effects of processing method, particle size, and mixing of different grains and(or) processing methods on feedlot performance will be discussed in this review.

The Effect of Rolling or Grinding Whole Corn

Grain in the dry form frequently is fed whole, rolled or ground. Starch digestibility and feed efficiency commonly is thought to be poorer for whole corn than rolled or ground corn (Ørskov, 1976; Theurer, 1986). However, a recent literature review concluded that whole corn fed in high concentrate diets resulted in faster and more efficient gains than rolled or ground corn grain (Owens et al., 1995). Whole or coarsely processed corn may serve to increase intake of animals early in the feeding period due to greater palatability (reduced dust) and more desirable feed texture (Eng, 1992). Slower fermentation may decrease the incidence of acidosis.

Vance et al. (1972) fed crimped or whole shelled corn with corn silage to growing and finishing beef steers. In diets containing either 31% roughage or no roughage, steers fed whole corn had higher gains and better feed:gain ratios than those fed crimped corn. At higher levels of corn silage, steers fed crimped corn had better gains and feed:gain ratios than those fed whole corn. Usually, whole corn is fed with very low levels of roughage; utilization of whole corn often is poorer with higher roughage levels (Owens et al., 1995). Vance et al. (1972) examined the rumen of cattle fed high concentrate diets for color, clumping of papillae and hair accumulation, all thought to be indicative of sub-clinical acidosis and lack of rumen health. Steers fed the crimped corn diets exhibited lower ruminal pH, a higher degree of abnormal rumen color, and clumping and hair accumulation in the papillae than steers fed whole corn. However, overall diet digestibility was not altered by the form of the corn grain. Additionally, Klay (1968), Meiske et al. (1968), and Hixon et al. (1969) all observed no difference in animal performance due to corn crimping when compared with cattle fed whole corn.

Clanton et al. (1980) compared whole shelled and dry rolled corn in a 92% concentrate 8% corn silage finishing diet for yearling steers. No difference was detected in animal performance or carcass characteristics. Switching from whole corn to rolled corn or vice versa at a point two-thirds through the feeding period also had no effect on performance. Brink et al. (1978) found that steers fed whole corn performed similarly to those fed rolled corn or a mixture of whole and rolled corn. Martin et al. (1971) fed corn whole, rolled and ground to steers in a 140 day feedlot trial. Cattle fed whole corn ate less feed and had slightly lower gains; no difference was detected in the feed:gain ratio. White et al. (1975a, b) fed 238 kg calves whole or ground corn in a high concentrate feedlot diet. There was no difference in DMI however, ADG and feed:gain ratio were superior for the whole corn diet.

Van Schaack et al. (1993) fed whole or ground corn to feedlot steers in a 161 day finishing trial. During the first 84 days, feed intake was lower and feed efficiency was improved for cattle fed whole corn. No difference was detected in the last half of the feeding period or overall in steer performance. Traxler et al. (1995) fed Holstein calves 75% corn (whole or cracked) diets during the growing phase and 85% corn (whole or cracked) diets during the finishing phase. In the growing period, steers fed whole corn had higher DM intakes than those fed cracked corn but ADG and feed efficiency did not differ. DM intake also was greater for steers fed whole corn during the finishing period. ADG and feed efficiency was not different. Combining the growing and finishing period, the authors concluded that steers fed whole shelled corn had higher ADG, intake and final weight than those fed cracked corn. Feed efficiency tended to be best for whole corn but this difference was not significant statistically. Carcass data were not different between the two groups.

Stanton et al. (1987) fed light (213 kg) calves for 218 days on high concentrate diets consisting of: 1)whole corn, 2) 67% whole corn:33% rolled corn, 3) 33% whole corn:67% rolled corn or 4) rolled corn. DM intake did differ among treatments during the first 112 days or overall. However, ADG was highest and feed efficiency best for cattle fed the 67% whole, 33% rolled corn mixture during the first 112 days and over the total trial.

In contrast, Brink et al. (1984) found no advantage in ADG or DMI from substituting rolled corn for whole shelled corn from 0 to 100% of the total grain. However, feed:gain ratio tended to be improved as the rolled corn fraction of the diet increased.

These studies suggest that whole corn has a feeding value equal or superior to that of dry processed corn. Although whole corn often results in lower DM intake, rate and efficiency of gain are usually equal or superior to those obtained with rolled or ground corn diets.

Comparisons of Steam-Flaked, High Moisture and Dry Grains

Wet processing methods (steam flaking and high moisture ensiling) typically increase ruminal and total tract starch digestibility, presumably due to increased starch solubility in the rumen, increased grain surface area, and gelatinization of the starch. More extensive starch digestion should increase energy availability and thereby improve efficiency of feed use (Theurer, 1986). In vitro starch disappearance has been shown to be positively correlated ($R^2 = .58$) with gain:feed ratio (Ladely et al., 1995). However, more extensive fermentation usually is associated with more rapid fermentation, and more rapid fermentation increases the incidence of metabolic disorders (Ørskov, 1976, 1986).

Ramirez et al. (1985) fed weanling calves (192 kg) 85% concentrate diets containing whole shelled corn, steam-flaked corn or whole steamed corn for 221 days. DM intake was greater for steers fed whole steamed corn than those fed whole or steam-flaked corn. ADG was greater for steers fed steam-flaked and whole steamed corn than those fed whole corn. Therefore DM conversion was improved for steam-flaked corn (5.06) over the other two diets (5.79 and 5.62 for whole steamed and whole corn respectively). No difference was detected in carcass characteristics. An extensive digestion trial confirmed that starch digestibility was higher for steam-flaked corn (99.1%) than for whole steamed

(93.8%) and whole corn (93.0%). Retention time in the rumen was highest for whole corn followed by whole steamed and steam-flaked corn. Undoubtedly, steam-flaking treatment improves digestion coefficients for corn and the efficiency of feed use by feedlot cattle. However, these data suggest than steaming alone is inadequate. To increase digestion and animal performance, the steaming process must be accompanied by rolling or flaking of grain which increases the surface area of the grain.

Gill et al. (1980) fed steers (314 kg) high concentrate diets composed of whole corn, high moisture corn or steam-flaked corn. During the first 70 days on feed cattle fed whole corn ate less feed, gained more weight and were therefore more efficient than steers fed high moisture corn or steam-flaked corn. However, in the last half of the feeding period (d 70-133), steers fed the processed corn (high moisture corn and steam flaked corn) tended to have better performance. Overall, steers fed whole corn early and steam flaked corn or high moisture corn late in the feeding period were most the efficient converters of grain to gain. Similarly, Galyean et al. (1992) found that steers fed whole corn gained more during the first 56 days of the finishing trial than those fed steam flaked corn. However, cattle fed steam flaked corn gained weight faster overall (0 to 112 days), ate less feed and were therefore more efficient than those fed whole corn. Similar results for the entire feeding period have been found with high moisture corn (Ladely et al., 1995). One of the problems with interpreting results of trials that involved a switch in diets at a midpoint is that differences in fill may erroneously alter calculations of rate and efficiency of gain.

Davis (1980) found that DM intake and ADG tended to be higher for cattle fed rolled high moisture corn than for cattle fed ground high moisture corn; however, feed efficiency was improved by grinding the high moisture corn. Oklahoma researchers reached reasonably similar conclusions. Cattle fed rolled high moisture corn had higher DM intake than those fed ground high moisture corn. However, no difference was detected in ADG or feed:gain ratio (Van Koevering et al., 1994).

Results of studies conducted with milo have been inconsistent. Davis (1982) concluded that rolled high moisture milo produced superior feedlot performance than the ground form. In contrast, Lee (1984) found better performance from ground than rolled high moisture milo.

These studies could be interpreted to indicate that a slower fermentation rate (dry corn or larger particle size) may improve animal performance during adaptation of cattle to high concentrate diets, perhaps the result of reduced incidence of acute or subacute acidosis leading to less intake variation (Stock et al., 1995) and thereby higher feed intakes early in the feeding period. However, later in the feeding period, more extensive processing is needed for optimum feed efficiency.

Particle Size Effects on Performance

Few studies have attempted to quantify the relationship between grain particle size and feedlot performance. As discussed earlier, smaller particles generally are fermented faster and more extensively in the rumen whereas larger particles may increase flow of starch to the small intestine for digestion there. Increased ruminal digestion usually results in higher total tract digestibilities, but may not always enhance animal performance (Owens et al., 1986). In addition to increasing the digestibility of grains, proper processing (particle size and distribution) may optimize the balance of ruminal and intestinal digestion and thereby improve the feed:gain ratio.

Hironaka et al. (1979) fed 60 crossbred steers (individually) a pelleted diet which was composed of ingredients with particles that had mean geometric diameters ranging from 476 to 1,525 μm. The mixtures were pelleted and fed. Feed intake and gain responded quadratically, increasing and then decreasing as particle size was increased. The initial increase in intake with the larger particle size matches the results seen for feed intakes early in whole corn feeding trials. Feed efficiency was similar among treatments and carcass characteristics were not different. Bloat was not encountered and the number of liver abscesses was similar among treatments. However, the incidence of rumenitis and abnormal papilla growth and papillary clumping was more frequent for steers fed the finer diet and decreased as the particle size increased. The grain particle size used in this study is difficult to quantify because the roughage as well as the grain was processed and other ingredients probably altered particle size. Although few commercial feedlots feed a pelleted diet to finishing steers, results of this study indicate that relatively small particle sizes, through their impact on subacute acidosis, may be increasing the rate of fermentation in the rumen.

Turgeon et al. (1983) conducted two experiments in which steers (300 kg) were fed diets containing one of three roughage levels (alfalfa-brome hay) and 5 corn particle size treatments. The corn particle sizes were: whole (5,977 μm), cracked (2,232 μm), fine ground (734 μm), whole plus cracked mixture (average 4,105 μm) and, whole plus fine mixture (average 3,356 μm). No interaction existed between corn particle size and roughage level. Steers fed the whole plus cracked corn diet had heavier final weight, higher ADG and improved feed:gain ratio when contrasted with the whole corn diet. Intakes were not different. When compared with the cracked diet, the whole plus cracked diet produced an improved feed efficiency but final weights, ADG and DM intakes were not different. Whole plus fine diet increased final weight, ADG and DM intake but did not improve feed efficiency. Performance from steers fed fine diets did not differ from those fed the whole plus fine diet. Overall, steers fed the whole plus cracked (4,105 μm) corn performed best; however, starch digestibility was highest with the fine diet. In this trial, maximum digestibility did not maximize performance. The particle size and distribution (actual values not reported) of the whole plus cracked corn diet presumably provided an optimum balance of ruminal and intestinal digestion.

Mader et al. (1991) conducted two experiments with high moisture corn. In experiment 1, high moisture corn was either stored whole (7,620 μm) and fed whole or rolled before feeding (3,970 μm), or stored and fed ground (3,300 μm). A fourth diet consisted of a mixture of 75% rolled or ground fed with 25% whole for a combined particle size of 4,860 µm). Cattle fed whole high moisture corn gained faster and had higher feed intakes than those fed processed corn. Cattle fed the mixture and those fed whole high moisture corn had a similar feed:gain ratios, but both were superior to that of cattle fed ground or rolled high moisture corn. Cattle fed rolled high moisture corn had a slightly better feed:gain ratio than those fed ground high moisture corn. Carcass differences were not significant. Again, the corn perceived to be most digestible in the rumen (digestion values not reported) produced the lowest feedlot performance. In this case the largest particle size (least ruminally digestible) produced the most rapid rate of gain. Differences in storage conditions (whole vs ground prior to ensiling) might account for some of these differences; however rolling the whole corn prior to feeding reduced performance. Stock et al. (1991) compared high moisture corn (72% DM) stored and fed whole (7,030 µm, 92.9% whole) or rolled (5,210 µm, 31.2 % whole) just prior to feeding after being ensiled whole in upright silos. DM intake was not affected but ADG and feed efficiency were improved 7 and 8 % respectively by rolling the high moisture corn prior to feeding it. The rolled corn fed by Mader et al. (1991) was much finer (3,970 µm) and drier (86.5% DM) than the rolled corn in this study. Rolled corn containing 31.2% whole kernels may provide the desired balance of digestion. One would expect particle size to be less important at higher moisture levels due to increased microbial access to the high moisture corn particles and result in an increased optimum particle size at higher moisture levels.

Mader et al. (1991) conducted three additional trials feeding dry whole corn, whole high moisture corn, a mixture (75% ground and 25% whole) high moisture corn, and ground high moisture corn. Cattle fed ground high moisture corn diets consistently had lower gains than cattle fed whole high moisture corn diets. Gains of cattle fed the mixture were intermediate. Intakes and feed to gain ratios were similar among treatment groups. Carcass values were not different. Results indicated that whole corn in finishing diets had a feeding value comparable to or greater than processed corn. Galyean et al. (1981) reported that particle size has more impact on DM and starch disappearance of dry rolled corn than of ground high moisture or steam-flaked corn. Therefore, feeding mixtures of high moisture corn types containing different particle sizes probably would not be as beneficial as feeding a mixture of dry corn with high moisture corn.

In studies conducted with milo, Newsom et al. (1968) fed finely ground (679 μm), coarsely ground (890 μm), or rolled (1,146 μm) milo in high concentrate diets. Steers fed the finely ground milo tended to have higher ADG than those fed the coarsely ground or rolled grain. Coarsely ground milo increased DM intake followed by fine and rolled. However, cattle fed rolled milo were more efficient than those fed the fine or coarsely ground grain. Similar to previously mentioned studies with corn, performance was best with the larger particle size despite a lower digestibility.

In contrast, Berry and Riggs (1971) found no difference in ADG due to fineness of grind of milo. However, cattle fed the smaller particle size ate less feed and were more efficient than cattle fed milo with a larger particle size. In addition, KS researchers (Brethour, 1983) concluded that finely (430 μm) ground milo enhanced the performance of feedlot steers compared with rolled (945 μm) milo. In a review, Brethour (1984) stated that compared with a coarsely rolled milo, fine rolling resulted in reduced feed intake and faster and more efficient gains. Results of studies which have compared finely rolled and finely ground milo have been inconsistent. Although fine grinding usually decreases both feed intake and rate of gain, effects on feed efficiency vary. Variability in results with milo may be due to the low digestibility of dry processed milo and the wide diversity in chemical and physical characteristics of different milo cultivars.

In general, smaller grain particle sizes do not improve animal performance, though they are likely more digestible. Compared with high moisture corn, dry corn must be processed to a smaller particle size to optimize efficiency. Very little research establishing a relationship between actual grain particle size and animal performance has been conducted.

Associative Effects of Grains and Processing Methods

Many commercial feedlots use several different grains and (or) processing methods in their feedlot diets. Advantages of providing a mixture are difficult to determine using in situ or in vitro techniques. However, because different grains and processing methods can differ in site, extent and rate of digestion, providing a mixture of complementary ingredients may help to stabilize fermentation in the rumen and flow of starch to the small intestine. Numerous feeding trials have been conducted to investigate the advantages of a mixture. Interpreting results of such feeding trials must be done with caution, however, because factors beyond site and extent of starch digestion may alter results. Generally, mixtures will increase the diversity of particle sizes in the diet. This can either simplify or complicate ration handling and bunk management. And differences in bunk and animal management can easily alter the incidence of metabolic problems, i.e., bloat and acidosis, which in turn will affect feed intake, animal performance and feed efficiency. Like mutual funds, compiling a mixture should minimize risk of a catastrophe associated with a single grain or processing method and may slightly enhance nutrient supply through complementary effects (moisture content, palatability, amino acids, vitamins, trace minerals), reduce physical reliance on specific equipment (e.g., a steam flaker, storage space and machinery for ensiling high moisture corn), and spread financial risk across different time periods (e.g., purchase of high moisture corn at harvest vs throughout the year for dry grain). But there is no inherent reason that diluting the ideal grain or processing method with something less than ideal should enhance productivity.

Lee et al. (1982) completed two trials in which steers were fed mixtures of whole and steam flaked corn ranging from 0 whole:100 steam flaked corn to 100 whole:0 steam flaked corn. In experiment 1, ADG was highest for the 100 and 75% whole corn diets.

DM intake reflected ADG with increased intakes in the 100 and 75% whole corn diets. Consequently, no difference was detected in feed to gain ratio. Carcass measurements data were not affected. However, fecal starch increased as the percentage of whole corn increased in the diet. In contrast to experiment 1, ADG in experiment was higher for steers fed lower proportions (0 and 25%) of whole corn than for steers fed higher proportions. Feed intake was similar for all groups, so feed efficiency was improved as the proportion of steam flaked corn in the diet increased. Carcass characteristics were not influenced by treatment. The author attributed the lower intake and poorer performance with the 100% steam flaked corn in the first experiment to poor quality of the steam flaked corn that was used. However, in both experiments, cattle fed the 25% whole:75% steam flaked corn diet performed as well as those in any treatment group. Hence, 25% whole corn can be substituted for steam flaked corn finishing diets with little impact on performance. The higher ruminal and total tract starch digestibilities reported in this trial with the 100% steam flaked diet indicate that the highest extent starch digestion did not translate to the highest level of animal performance.

Sindt et al. (1987) conducted feeding trials where high moisture corn was mixed with a dry rolled grain (corn or milo). Feedlot gain and feed efficiency were improved 3 to 4% by feeding mixed diets over those with 100% high moisture corn. Similar results were recorded by Kreikemeier et al. (1987). Cattle fed a mixture of dry rolled corn (33 or 67%) and dry rolled wheat (67 or 33%) gained 4% faster and 4.4% more efficiently than the average performance of cattle fed 100% corn or wheat.

Stock et al. (1987) found complementary effects of mixing 67-75% high moisture corn with 33-25% dry corn (whole or rolled) on feedlot performance. Steers fed mixed diets gained 2.7% faster and 4.6% more efficiently than that predicted from the performance of cattle fed high moisture or dry corn (whole or rolled) alone. Cattle in a metabolism study fed a combination of high moisture corn and dry rolled sorghum, had greater digestion both in the rumen and the total digestive tract. Thus, a portion of the complementary effect of grain mixtures may be due to an increase in starch utilization. This may be due to ruminal complementarity among bacterial types. McAllister et al. (1990) has indicated that strains of ruminal bacteria that attach to and digest one grain may be completely different than those that ferment a different grain.

Wheat and high moisture corn were fed singly and in three combinations; wheat was either dry rolled or steam flaked (Bock et al., 1991). Adding dry rolled wheat to high moisture corn linearly decreased ADG while DM intake responded cubically. Feed to gain ratio and carcass characteristics did not differ. Substituting steam flaked wheat for high moisture corn diets did not affect animal performance. Starch from the 100% wheat diet fermented in the rumen twice as fast from as the 75 or 100% high moisture corn diets. Rate of starch digestion of grain mixtures was related inversely to DM intake and gain to feed ratio. The author concluded that increased performance may be associated with decreased rate of ruminal starch digestion.

Compared with feeding very rapidly fermented feeds, e.g., 100% high moisture or steam flaked corn or wheat, grain mixtures may slow the rate of digestion in the rumen and thereby reduce the incidence of acidosis. In addition, mixtures might increase the flow of starch to the small intestine. Grain mixtures may allow for improved ruminal digestion of the slower digesting grains and partition the site of digestion to achieve an optimum balance between ruminal an small intestinal digestion. These concepts are supported by the increases animal performance sometimes observed with mixtures of grains or processing methods. A similar result might be obtained by providing a single grain or processing method that provides a wider distribution of particle sizes. Differences in fermentation rate among particles of different sizes might provide a similar boost in animal performance.

Table 1. Advantages and disadvantages of ruminal and small intestinal starch digestion.

Starch Digestion Site	Advantages	Disadvantages
Rumen	High total tract digestibility	Increased health concerns
	Easy to maximize	-acidosis
	Decreased fermentation loss	-liver abscess
	-cecum	-laminitis
	-large intestine	-polioencephomalacia
	Increased microbial protein flow	Lower energy utilization
Small Intestine	Improved energy utilization	Low total tract digestibility
	Reduced health concerns	Difficult to find optimum
	Reduced processing cost	Digestion may be limited
		Reduced protein flow

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CHAPTER III

IMPACT OF CORN PARTICLE SIZE ON PERFORMANCE OF FEEDLOT STEERS

ABSTRACT: Angus crossbred steers (n=33, 353 kg.) were fed corn rolled to one of three different particle sizes. The steers, housed in 15 different pens, were given ad libitum access to an 86% concentrate, 14% cottonseed hull diet for 145 d. Only the grain particle size differed. All corn (86.0 % DM) was rolled through stacked rolls; clearance between the rollers was adjusted to produced three different but uniform grain particle sizes. The coarsely (C) rolled particles had a geometric mean diameter (GMD) of 2,598 $\pm$ 1.71 microns (μm) was slightly finer than most commercially processed rolled corn. For the medium (M) and fine (F) particle sizes, corn grain was rolled to 1,545 $\pm$ 1.83 and 756 $\pm$ 1.86 μm, respectively. Particle size did not alter DMI by steers, but ADG and feed efficiency tended to respond quadratically, being best (1.56 kg, P = .24 and 5.9, P = .16) with the intermediate particle size. Marbling score was highest (P = .02) with 91.0% of steers grading choice with the medium particle size; no treatment responses in backfat thickness, KHP or yield grade were detected. Diet DM digestibilities did not differ significantly between treatments although starch digestibility (95.3, 96.3 and 97.6 % for F, M and C) increased (P = .03) as particle size decreased. Results of quadratic regression across these particle sizes suggested that to optimize feed efficiency, corn should be rolled to a GMD of 1,628 μm whereas rate of gain would be maximum with 1,744 μm. During the first half of the study, C tended to produce the highest DMI and ADG whereas during the last half of the trial, ADG tended to be highest with F. A particle size much finer than fed commercially optimized performance, efficiency and marbling by feedlot steers.

(Key Words: Corn, Particle size, Feedlot)

Introduction

Corn processing and particle size can influence digestibility and cattle performance (Hale, 1973). Finely ground grains are more rapidly and extensively fermented in the rumen than coarser grains. However, with coarsely ground grain, flow of starch to the small intestine may increase which in turn may increase energetic efficiency (Owens et al., 1986). Hence, maximum digestion may not yield optimum feed efficiency. Furthermore, finely grinding grain, to increase digestibility, typically increases the risk of acidosis which may affect performance adversely (Ørskov, 1986). This balance between a fine particle size which will maximize ruminal and total tract digestibility and a coarse particle size which will minimize metabolic disorders associated with rapid ruminal fermentation and increase starch flow to the small intestine appears critical. This balance may be achieved through processing grain to an optimum particle size for maximum cattle performance; impact of particle size on performance of feedlot cattle has not been addressed in the literature. Differences among roughage sources and roughage concentrations, among grain types and grain processing methods, and among cattle types and ages has complicated this task. The purpose of this trial was to examine the impact of corn particle size on the performance of yearling feedlot steers.

Materials and Methods

Thirty-three predominately black, Angus, Salers and Hereford crossbred steers (353 kg) were obtained in the fall of 1993. These yearlings had grazed native range in Osage County, OK during the preceding summer. On December 2, 1993 (d 0) the steers were weighed, dehorned (if necessary), vaccinated with an 8-way clostridial killed bacterin and implanted with Synovex-S® (200 mg progesterone, 20 mg estradiol benzoate; Syntex, West Des Moines, IA). Following weighing, these animals were stratified by weight and assigned randomly to one of three treatments. All cattle were adapted to full feed on an

86% concentrate diet (Table 2) by d 14. Eighteen indoor pens (6 pens per treatment) with slatted floors were used with 15 pens housing two steers each and three pens housing individual steers. Steers were reimplanted on d 88 with Synovex-S®.

The diet (Table 2) was available for ad libitum consumption with fresh feed added once each day. Diets differed only in the degree of corn processing before the other components were added. Corn was rolled with a stack roller system (2 roller pairs) provided by Automatic Feed Mfg. Co., Pender, NE. Corn samples were taken weekly; geometric mean diameter was determined at a commercial laboratory by the method of Ensor et al. (1970). Geometric mean particle size for the three treatments are shown in Table 3. Orts were weighed, discarded weekly and subtracted from the total feed intake. The final diet contained 14% cottonseed hulls. This roughage concentration purposely was higher than used in commercial feedlots with the intention of preventing acidosis and depressed feed intakes often associated with finely ground diets. This should permit us to examine effects of particle size without having the complication of different feed intakes with the different diets. Metabolizable and net energy values for the diet were calculated using ADG, DMI and mean animal weights by iteratively solving the NRC (1984) net energy equation for large frame steer calves.

The average of the two weights taken on d 0 and d 1 was used as a starting weight. Interim weights were measured on d 28, 61, 88, 116 and 144 of the trial with 4% pencil shrink applied for calculation of gain and feed efficiency. The carcass-adjusted final weight was calculated by dividing hot carcass weight by 0.645 (average dressing percentage, 64.5%). ADG during the first half (d 61) of the feeding period was calculated as the slope of the regression line (d 0, d 28 and d 61). ADG during the second half (d 62 through d 145) was calculated in the same manner using weights obtained on d 88, d 116 and the carcass-adjusted final weight. ADG for the total feeding period was calculated from the average weight on d 0 and d 1 and the carcass-adjusted final weight. Feed intake was expressed as the mean DM intake (DMI) over the period divided by the number of animals in the pen. Feed efficiency was expressed as the ratio of total pen DMI to total pen gain.

Fecal grab samples were obtained from each steer at each weighing. Fecal samples were dried at 100 °C for 48 h, ground through a 2 mm screen, and analyzed for starch (MacRae and Armstrong, 1968), protein (AOAC, 1990), and purine content (Zinn and Owens, 1986). Cottonseed-hull based pellets containing chromic oxide were top-dressed from d 132 to d 142 to provide each animal with 10 g chromic oxide daily. Fecal grab samples from each steer were taken at 0700 and 1600 on d 139, 140 and 141. Samples were composited across time and analyzed for chromium concentration (Hill and Anderson, 1958), starch, and protein content. Total tract digestibilities for DM, starch and protein were calculated.

All animals were slaughtered at a commercial packing facility (Excel Corporation, Dodge City, KS) on d 145. Carcass data were collected following a 48 hr chill. The following measurements were obtained: 1) longissimus area, measured by direct grid reading of the longissimus at the 12th rib; 2) subcutaneous fat over the longissimus at the 12th rib, taken at a location 3/4 the lateral length from the chine bone end; 3) kidney, pelvic and heart fat (KPH) as a percentage of carcass weight, and 4) marbling score (USDA, 1965). Using these values, yield grades were calculated.

This study was constructed as a randomized complete block. The steers were blocked according to initial weight into 6 weight blocks. The data were analyzed by GLM procedures of SAS (1988) with pen as the experimental unit. The model included block and particle size. Linear and quadratic effects were separated by orthogonal contrasts for unequally spaced numeric variables (particle size).

Results and Discussion

The effects of particle size on feedlot performance are summarized in Table 3. No significant differences were detected in performance from d 0 to d 61, but quadratic trends were noted for ADG ($P = .12$) and feed efficiency ($P = .21$) from d 62 to d 144. Over the entire feeding period, quadratic trends were seen in ADG and feed efficiency. In each of these cases, steers fed the medium particle size had slightly greater ADG (9%) but similar feed intake which resulted in a slight improvement (8%) in feed efficiency. Hironaka et al. (1979) found that steers fed the coarser material had higher intakes and gain early in the feeding period but this advantage was lost later in the feeding period. NEg of the diet, calculated from DMI, ADG, and mean weight, was 106 to 114% that calculated from individual feed ingredients (NRC, 1984) composing the diet (Table 2). Results can be interpreted to suggest that ADG and feed efficiency were slightly superior for the medium particle size as compared to finer or coarser corn particles.

Turgeon et al. (1983) compared diets containing mixtures of coarsely rolled and whole corn. The mixture at 4,105 μm produced a greater rate and efficiency of gain than whole corn and tended to be superior to coarsely rolled corn alone. Finely rolled corn (734 μm) adversely affected intake, ADG and feed:gain ratio as did the fine rolled-whole corn mixed diet (3,356 μm). Though particle sizes used in their trial are larger than ours, a similar effect (medium particle size produced superior feed efficiency) was seen. Obviously the presence of whole corn kernels complicates the effect of particle size. Chewing during eating and rumination will reduce particle size much more for whole corn than for mechanically processed corn (Ewing and Johnson, 1987). Therefore the differences in particle size entering the rumen used in the present study and those utilized by Turgeon et al. (1983) probably are not as great the differences noted for the diet. Turgeon et al. (1983) also used a much lower roughage level (5 vs 14%); this may account for the difference in findings and suggests that with higher dietary roughage levels particle size must be less to attain optimum performance. Certainly, fine particles are desirable with the higher roughage diets typically fed to lactating dairy cows (Bush et al., 1972).

Table 4 summarizes the carcass characteristics. Only marbling score varied among treatments, exhibiting a quadratic effect. Cattle fed the medium particle size had a higher ($P = .02$) marbling score. The additional energy these animals extracted from the diet and(or) a more optimum site of digestion may be responsible for increased marbling with no increase in backfat or KHP although no specific mechanism for this effect or previous literature supporting such a finding was located.

Table 5 presents the regressions of performance against particle size. Maximum values were determined by taking the first derivative of the regression lines calculated using both the linear and quadratic components (regardless of significance). For maximum feed intake, the quadratic regression predicts that the optimum particle size is considerably larger than that required for maximum ADG or minimum feed:gain. Maximum ADG also should occur with a larger particle size than optimum efficiency. Subdividing the feeding trial into the first and second half revealed that the particle size calculated to maximize intake, gain and efficiency for the first half of the feeding period was larger than for the second half of the feeding period. This may be reflect reduced chewing by older animals as noted previously by DeBoever et al. (1990). For the total feeding period, maximum intake was estimated to occur with a corn particle size of 2,276 μm. Gain was predicted to be maximized at 1,744 μm, and efficiency was optimal at 1,628 μm. Calculated ME and NEg peaked at geometric mean diameters of 1,655 μm and 1,641 μm, respectively. These results indicate that a larger particle size may be optimal early in the feeding period whereas a reduced size may optimize energy utilization later. These optimum particle sizes also might change with roughage level and type and animal age.

Diet digestibilities and fecal compositions are summarized in Table 6. Dry matter digestibility tended to be greater with fine and medium than with coarse corn particles. Starch digestibility increased linearly ($P = .03$) as particle size was decreased. Despite the increased starch digestibility, less rapid and efficient gains with finer particles may indicate that fine particles were too extensively digested in the rumen and that site of digestion may be important in maximizing efficiency. Certainly, the fine rolled corn is likely to be digested more extensively in the rumen than medium or coarse rolled corn (Waldo, 1973). Medium rolled corn may have been digested to a greater extent in the small intestine than fine. If small intestinal digestion is more efficient than ruminal fermentation (Owens et al., 1986), efficiency should be improved by achieving a proper balance between ruminal and intestinal digestion. Fecal starch concentration was higher for medium and coarse than the finely ground corn. Starch concentration of the feces is an additional indication of starch utilization (Zinn, 1992). Purine concentration in the feces also was measured which may reflect microbial growth in large intestine (Zinn and Owens, 1986). Purine concentration in feces tended ($P = .23$) to increase as particle size decreased. Protein content of the feces also tended ($P = .07$) to increase as particle size decreased. These factors may reflect the greater digestibility of the smaller particles reaching the large intestine from the finely rolled corn. Larger particles in the large intestine may not be as easily attacked by microbes in the large intestine as small particles.

Although cattle fed the finely rolled corn exhibited a feed efficiency slightly inferior to those fed a medium particle size, digestibility data indicate that starch digestion was greatest for the finest corn. Considering the high roughage level we fed, it seems unlikely that these cattle were experiencing sub-clinical acidosis. However, the balance of digestion may have shifted slightly from the rumen to the small intestine by the medium particle size.

Implications

Rolling corn grain to a medium rather than a fine or a coarse particle size tended to improve feed and energetic efficiency, and marbling score of feedlot cattle. Finer grinding resulted in the highest starch digestibility. For optimum gain, during early stages of a finishing period a larger particle size may prove beneficial for maximum feed intake. But later in the feeding period, a smaller particle size tends to improve efficiency, perhaps because extent of chewing and rumination decreases as cattle age. Because roughage level and source, animal age, and grain moisture content all may alter results, these findings may apply only to large framed yearling steers fed dry corn diets containing 10 to 15% cottonseed hulls. However, these results illustrate that particle size of grain may affect feedlot performance and that maximizing starch digestibility does not necessarily optimize efficiency of feed use.

Table 2. Diet and calculated nutrient composition (% of DM).

Ingredient	% of diet DM
Corn, dry rolled	76.78
Cottonseed hulls	14.00
Soybean meal	7.66
Limestone	.77
Urea	.46
Salt	.28
Manganous oxide	.003
Vitamin A-30	.01
Rumensin-60	.02
Tylan-40	.01
Calculated nutrient content, DM basis	
NEm, Mcal/kg [a]	1.99
NEg, Mcal/kg [a]	1.32
Crude protein , %[b]	12.70
Potassium, %	.63
Calcium, %	.35
Phosphorus, %	.26
Magnesium, %	.147
Cobalt, ppm	.064
Copper, ppm	6.6
Iron, ppm	61.2
Manganese, ppm	44.7
Selenium, ppm	.176
Zinc, ppm	20.9

[a] NEm and NEg based on values for ingredients from NRC (1984).
[b] Crude protein was based on Kjeldahl analysis of individual feeds.

Table 3. Particle size effects on feedlot performance data : linear (L) or quadratic (Q) functions .

Item	Fine 756µm	Medium 1,545µm	Coarse 2,598µm	SEM	*P* =
Weight, kg					
Initial[a]	352	355	353	8.2	Q, .78
Day 61[a]	452	461	464	12.7	L, .57
Final[b]	557	579	561	19.5	Q, .29
ADG, kg					
Day 0 to 61	1.95	2.06	2.14	.14	L, .55
Day 62 to 144	1.04	1.18	.91	.12	Q, .12
Total[b]	1.41	1.56	1.45	.11	Q, .24
DMI, kg					
Day 0 to 61	8.5	8.7	9.0	.38	L, .82
Day 62 to 144	10.3	10.5	10.5	.32	L, .79
Total	8.9	9.1	9.2	.31	L, .59
Feed/gain					
Day 0 to 61	4.4	4.2	4.2	.19	L, .36
Day 62 to 144	9.1	8.1	11.4	1.4	Q, .21
Total[b]	6.3	5.9	6.5	.37	Q, .16
Calculated diet energy					
ME, Mcal/kg	3.19	3.35	3.16	.11	Q, .13
NEg, Mcal/kg	1.42	1.51	1.40	.06	Q, .14

[a]Live-weight with a 4% shrink.
[b]Calculated using carcass weight and average dressing percentage.

Table 4. Particle size effects on carcass characteristics: linear (L) or quadratic (Q) functions .

Item	Fine 756µm	Medium 1,545µm	Coarse 2,598µm	SEM	*P* =
Hot carcass wt, kg	357	368	362	9.1	Q, .48
Dressing percentage	64.1	63.5	64.9	.79	Q, .36
Yield grade	2.9	2.6	2.5	.19	L, 16
Marbling score[a]	425	524	457	26	Q, .02
Choice, %	91.7	91.7	83.3	9.1	L, .51
Select, %	8.3	8.3	16.7	9.1	L, .51
REA, cm^2	83.8	88.4	89.2	2.8	L, .26
KPH, %	1.7	1.5	1.5	.19	L, .68
Back fat, cm	1.5	1.4	1.4	.13	L, .28

[a]Select > 300, Choice > 400, Prime > 600.

Table 5. Estimated optimal particle size (PS) to maximize performance parameters.

Item	Calculated PS (microns)	Regression Equation
ADG		
Day 0 to 61	2,396	$Y = 3.83 + 7.0x10^{-4}$ PS - $1.4\ x10^{-7}$ PS^2
Day 62 to 144	1,591	$Y = 1.39 + 1.5x10^{-3}$ PS - $4.6\ x10^{-7}$ PS^2
Total	1,744	$Y = 2.43 + 1.1x10^{-3}$ PS - $3.3\ x10^{-7}$ PS^2
DMI		
Day 0 to 61	3,908	$Y = 18.39 + 7.0x10^{-4}$ PS - $9.0\ x10^{-8}$ PS^2
Day 62 to 144	2,055	$Y = 18.87 + 1.9x10^{-3}$ PS - $4.7\ x10^{-7}$ PS^2
Total	2,276	$Y = 18.66 + 1.4x10^{-3}$ PS - $3.1\ x10^{-7}$ PS^2
Feed/gain		
Day 0 to 61	2,044	$Y = 4.86 - 6.7x10^{-4}$ PS + $1.6\ x10^{-7}$ PS^2
Day 62 to 144	1,508	$Y = 12.69 - 5.9x10^{-3}$ PS + $2.0\ x10^{-6}$ PS^2
Total	1,628	$Y = 7.49 - 1.9x10^{-3}$ PS + $5.9\ x10^{-7}$ PS^2
Calculated energy		
ME	1,655	$Y = 2.81 + 6.3x10^{-4}$ PS - $1.9\ x10^{-7}$ PS^2
NEg	1,641	$Y = 54.71 + 1.6x10^{-2}$ PS - $4.9\ x10^{-6}$ PS^2

Table 6. Particle size effects on diet DM digestibility and fecal components: linear (L) or quadratic (Q) functions .

Item	Fine 7,56 µm	Medium 1,545 µm	Coarse 2,598 µm	SEM	*P* =
Digestibility, %					
Dry matter	77.8	77.8	74.4	1.93	L, .21
Starch	97.6	96.3	95.3	.64	L, .03
Fecal concentration of DM, %					
Crude protein	13.8	13.9	11.7	.80	L, .07
Purine	.48	.49	.44	.04	L, .23
Starch	8.1	11.2	12.2	.64	L, .05

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CHAPTER IV

ROLLED VERSUS WHOLE CORN FOR FEEDLOT STEERS

Abstract: Growing steers were used in a feeding trial and a metabolism trial to examine the effects of corn form and feed intake level on feedlot performance and ruminal parameters. In the feeding trial, we used 144 steer calves (245 kg) in a 3 by 2 factorial arrangement of treatments to test effects of form of corn grain (finely rolled - 1,550 μm; coarsely rolled - 3,100 μm and whole - 5,700 μm) fed ad libitum or restricted to 83% of ad libitum for the first half of the feeding period. Due to potential interaction, simple effects were examined. For cattle given ad libitum access to feed, DMI tended to be highest with coarsely rolled corn in the first half of the feeding period and overall (quadratic, $P = .07$ and $P = .10$, respectively) with the coarsely rolled corn producing the fastest gains (quadratic, $P = .04$). However, feed efficiency tended to be improved by larger grain particle sizes (linear effect, $P = .10$). Steers ad libitum fed the coarsely rolled corn had heavier carcasses (quadratic, $P =.02$) and more internal fat (quadratic, $P < .01$) than cattle fed finely rolled or whole corn diets. For the limit fed steers, particle size did not significantly alter DMI, ADG, feed efficiency, or carcass measurements. Concentration of starch in feces, an index of indigestibility, increased linearly ($P = .03$) as particle size was increased both with limit fed and ad libitum fed steers, primarily due to lower starch concentrations in feces of ad libitum fed steers consuming finely rolled corn. In the metabolism trial, measurements were taken from three ruminally cannulated steers in a 3 X 3 replicated Latin square fed the same diets used in the feeding trial. Ruminal pH tended to be lower (linear effect, $P = .06$) with whole corn diets at feeding (24 h after fresh feed was provided). However, at 4 and 12 h post-feeding, pH ranking was precisely opposite with pH being highest with larger particle size corn (linear effect, $P < .01$). Total VFA concentrations in the rumen were inversely related to ruminal pH, being highest (linear effect, $P = .07$) with whole corn at feeding (24 h since the last meal); not different at 4 h post-feeding, but precisely

reversed at 12 h post-feeding (linear effect, $P < .01$) being lowest in steers fed the whole corn. The acetate to propionate ratio increased with increasing particle size at 4 h and 12 h post feeding. Lactate production tended to be highest (linear effect, $P = .10$) with finely rolled corn. The results of both experiments suggest that an increased extent of ruminal fermentation, as indicated by higher total VFA concentrations and a higher proportion of propionate did not equate to improved feedlot efficiency. Compared with dry processed corn, whole corn produced an equal rate of gain and a superior feed efficiency. However, limiting feed intake reduced or eliminated the effect of particle size on feed efficiency. (Key Words: Whole corn, Feedlot, Particle size, Fermentation)

Introduction

By influencing the site and extent of digestion, corn particle size can alter performance of cattle (Hale, 1973) as has been demonstrated repeatedly in feedlot studies (Hironaka et al., 1979; Turgeon et al., 1983; Secrist et al., 1995). Particle size is one factor inherently involved in determining the rate and extent of starch digestion in the rumen and total tract (Waldo, 1973). When extent of ruminal starch digestion is increased, total tract digestion of starch usually increases (Hale, 1973). However, carbohydrate digested by mammalian enzymes in the small intestine may be more efficiently utilized by ruminants (Owens et al., 1986; Nocek and Tamminga, 1991). Compared with finely ground corn, whole and coarsely processed corn will present an increased quantity of starch to the small intestine (Galyean et al., 1979). Compared with rolled corn, whole corn may enhance efficiency of gain of cattle fed high concentrate diets (Owens et al., 1995). The objectives of these experiments were to investigate the effects of limit vs ad libitum feeding of corn grain processed in various manners (rolled to one of two particle sizes or fed whole) on the performance and carcass characteristics of growing steers (experiment 1), and on the ruminal environment of yearling steers given ad libitum access to feed (experiment 2).

Materials and Methods

Experiment 1. Predominately black, Brangus X English crossbred, fall born steers (N = 144) were received in either July, September or November of 1994 at feedlot research facilities at Stillwater, OK. The calves all originated from the same ranch in northeastern OK. At weaning (June 1994) the calves were stratified by weight and assigned randomly as blocks to either: 1) go directly to the feedlot in July, 2) graze native range until entering the feedlot in September or 3) graze native range until entering the feedlot in November. Upon arrival at the feedlot, steers in each time block (n = 48) were weighed, vaccinated with a modified live virus 4-way respiratory and 7-way clostridial vaccine. After weighing, steers were stratified by weight and allotted randomly to treatment and pen ensuring an equal weight distribution in each pen within each block. The treatments were arranged in a blocked 3 X 2 factorial with date entering the feedlot serving as the block. Three corn processing treatments (finely rolled, coarsely rolled, or whole corn) were provided for steers to consume ad libitum (ADLIB) or in a quantity limited (LIM) and fed once each day at a rate proportional to the quantity of feed consumed by ADLIB cattle the previous 14 days.

The steers were housed (8 head/pen) in 18 outside pens (6 pens/block and 3 pens/treatment combination) with slated floors and covered cement fenceline feedbunks. Pen was used as the experimental unit. Table 7 contains relevant days on feed and implant data. All calves were implanted twice (Synovex-S® followed by Revalor-S®) to insure a similar number of days on the final implant before slaughter. The cattle were dewormed with a feed-borne antihelmintic (Safeguard®) after feed intake had stabilized.

Isocaloric and isonitrogenous dry corn based diets (Table 8) were fed once daily (4 p.m.). The basal ingredients (corn, cottonseed hulls and protein supplement) were analyzed for DM, crude protein and starch. The diets differed only in the extent of corn processing. Quantity of feed provided to pens of cattle that were limit fed was equal to

90% of the previous two week mean DMI of the corresponding ADLIB pens within each block. Because of the time lag between ADLIB and LIM cattle, limit fed pens received an average of 83% of the intake of ADLIB fed pens until steers had gained approximately 136 kg in full body weight which was approximately the first half of the feeding period. During the second half of the feeding period, LIM steers were allowed ad libitum access to feed.

Corn was rolled with a stacked roller system (2 roller pairs) provided by Automatic Feed Mfg. Co., Pender, NE. Corn samples were taken weekly and geometric mean diameter was determined at a commercial laboratory using the method of Ensor et al. (1970). Geometric mean particle sizes were: 1,550 µm (fine), 3,100 µm (coarse) and 5,700 µm (whole). Fecal samples were collected from each pen at each weighing (monthly) and dried at 100°C for 48 h. These samples then were ground through a 2 mm screen and analyzed for starch (MacRae and Armstrong, 1968). protein (AOAC, 1990), and nucleic acid nitrogen (purine) content (Zinn and Owens, 1986).

Steers were weighed following transport to the feedlot (5 hours) and at 28 d intervals thereafter. The carcass-adjusted final weight was calculated by dividing hot carcass weight by 0.635 (average dressing percent, 63.5%). A 4% pencil-shrink was applied to all live weights (except d 0) prior to calculating ADG. ADG during the first half (approximately 90 d) of the feeding period was calculated as the slope of the regression line through the corresponding interim weights. Second half (approximately d 90 until slaughter) gain was calculated in the same manner using interim weights and the carcass-adjusted final weight. ADG for the total period was obtained using the off-truck weight (d 0) and the carcass-adjusted final weight. Feed intake was expressed as the mean DM intake over the period divided by the number of animals in the pen. Feed efficiency was expressed as the ratio of pen DMI to total pen gain. Metabolizable and net energy values for the diet were calculated using ADG, DMI and mean animal weights by iteratively solving the NRC

(1984) net energy equation for large frame steer calves. Pen means were used for statistical analysis.

All animals were slaughtered at a commercial packing facility (Excel Corporation, Dodge City, KS). Carcass data were collected following a 48 hr chill. The following measurements were obtained: 1) longissimus area, measured by direct grid reading of the longissimus at the 12th rib; 2) subcutaneous fat over the longissimus at the 12th rib, taken at a location 3/4 the lateral length from the chine bone end; 3) kidney, pelvic and heart fat (KPH) as a percentage of carcass weight, and 4) marbling score (USDA, 1965). Yield grades were calculated from these measurements.

This study was constructed as a completely randomized block, with a 3 X 2 factorial arrangement of treatments with pen as the experimental unit. Date on feed (July, September, November) served as the blocking factor. The data were analyzed by general linear models procedures of SAS (1988) using the pen as the experimental unit. Model effects included block (date placed on feed), particle size of the corn (PS), level of feeding (FM) and the PS by FM interaction. Linear and quadratic effects of block and PS were separated using orthogonal contrasts when numerical variables were unequally spaced (PS). These contrast coefficients were calculated by the method of Steel and Torrie (1980).

Experiment 2. Three yearling beef steers (408 kg) fitted with permanent ruminal cannulae were housed individually in outdoor pens with slatted floors and cement fenceline feedbunks. Three particle size treatments (fine rolled, coarse rolled and whole corn) were tested in a replicated 3 X 3 Latin square design using the processing methods and particle sizes as described in experiment 1. All diets were available ad libitum with fresh feed being provided at 8:00 a.m. Cottonseed-hull based pellets containing chromic oxide were fed to each animal to provide 10 g chromic oxide per day. Following 7 d for adaptation, ruminal and fecal samples were obtained at feeding and at 4 h and 12 h post-feeding. To evaluate rate of eating, feed remaining in the bunk was weighed at 4, and 12 h after fresh feed was provided; this feed was returned to the bunk after sampling.

Ruminal samples were strained through 4 layers of cheese cloth and pH was measured immediately. A 5 mL aliquot was mixed with 250 mg of metaphosphoric acid (Erwin et al., 1961) in preparation for VFA analysis. Volatile fatty acids were analyzed by gas chromatography (Harmon et al., 1985). A 5 mL aliquot was mixed with 5 mL of 20% trichloroacetic acid solution to conserve it for lactate analysis. Lactate (both D and L isomers) were analyzed by spectrophotometric procedures (COBAS MIRA Chemistry Systems, St. Louis, MO).

Fecal grab samples were obtained from each steer at each sampling and composited across time, within sampling day. Fecal samples were dried at 100°C for 48 h. These samples then were ground through a 2 mm screen and analyzed for starch (MacRae and Armstrong, 1968). protein (AOAC, 1990), purine (Zinn and Owens, 1986), and chromium (Hill and Anderson, 1958) concentrations. Total tract DM and starch digestibilities were calculated.

Results were analyzed by GLM procedures of SAS (1988). The model included replicate, steer, sampling period and particle size treatment. Linear and quadratic effects were examined by orthogonal contrasts for unequally spaced numeric variables as described in experiment 1.

Results and Discussion

Experiment 1. The effects of corn particle size on feedlot performance are summarized for ADLIB and LIM in Tables 9 and 10, respectively. Particle size by feed intake interactions (Tables 9, 11 and 13) indicated potentially significant effects. Therefore, we examined simple effects in order to determine if ad lib feeding might accentuate the effect of corn particle size. DMI for ADLIB (Table 9) during the first half of the feeding period (period 1) tended (P = .07) to respond quadratically with the coarsely rolled corn tending to have the highest DMI by about 13%. In the second half (period 2) only slight numerical differences were detected; however, averaged over the total trial, a quadratic trend ($P = .10$) in DMI was observed with DMI being 8.6% greater for the coarsely rolled grain over the total trial. DMI for LIM were controlled for the first half of the study; over the total trial, intakes were only slightly higher (4%) for the coarsely rolled grain, a difference that can attributed almost completely to the first half of the study. In some trials, DMI has been lower with whole than processed corn (Martin et al., 1971; Van Schaack et al., 1993) but Traxler et al. (1995) observed that DMI was greater for whole than processed corn. In most studies, DMI has been virtually equal whether the corn was fed whole, rolled, or ground (White et al., 1975a and 1975b; Brink et al., 1978; Clanton et al., 1980; Turgeon et al., 1983; Brink et al., 1984; Stanton et al., 1987)

ADG response of ADLIB steers to PS reflected differences in DMI tending to be quadratic for both period 1 ($P = .13$), period 2 ($P = .14$) and over the total trial ($P = .04$). Similarly, final weights (both live and carcass adjusted) exhibited a significant quadratic effect with steers fed coarsely rolled corn being the heaviest. LIM cattle responded similarly in period 1, but in period 2, gains tended to increase ($P = .20$) with an increasing particle size. Averaged across the total trial, particle size had no effect on ADG of LIM steers.

Feed efficiency tended to respond linearly with particle size in period 1 ($P = .11$) and across the total trial ($P = .09$) with a 12% and a 7% advantage for whole corn over the mean of the two rolled forms of grain. However, particle size had no effect on feed efficiency during period 2. Feed efficiency calculated for LIM steers mirrored that of ADLIB, though differences were not significant. NEg of the diet, calculated from DMI, ADG, and mean weight of ADLIB steers, was 97 to 108% that calculated from individual feed ingredients (NRC, 1984) composing the diet (Table 8). Results can be interpreted to suggest that ADG and feed efficiency were slightly superior for whole corn as compared to fine or medium corn particles.

No information was located in the published literature that had examined the effect of grain particle size on both limit fed and ad libitum fed cattle. In published studies with ad libitum feed intake, whole corn often has produced higher ADG and improved feed efficiency when compared with dry processed (rolled, ground, crimped, cracked) corn (White et al., 1975a, b; Vance et al., 1972; Traxler et al., 1995). Van Schaack et al. (1993) reported that rate and efficiency of gain were greater with whole corn during the first 84 d of a 112 d feeding trial. However, other research has detected either no advantage (Klay, 1968; Meiske et al., 1968; Hixon et al., 1969; Brink et al., 1978; Clanton et al., 1980; Brink et al., 1984) or a disadvantage (Turgeon et al., 1983; Stanton et al., 1987) for whole vs dry processed corn. In a recent review, Owens et al. (1995) concluded that for cattle fed high concentrate diets, efficiency of gain was greater for whole than dry rolled corn. Our results concur with that observation.

Limit feeding appeared to have a larger impact with cattle fed smaller particle sizes. The limit feeding advantage in feed efficiency during the first half of the feeding period decreased as particle size increased (8% vs 3% vs -1% for FR, CR and WC, respectively). Limit fed cattle exhibit more aggressive behavior at the feed bunk and likely consumed their feed more quickly. This may have led to decreased chewing and lowered starch utilization. Limit feeding may require more extensive grain processing to achieve optimum performance than full-fed cattle.

Carcass data are summarized in Tables 11 and 12. The only differences noted in carcass characteristics were quadratic effects of particle size on carcass weight and KPH, both of which were greater for ADLIB steers fed coarsely rolled corn. Similar trends for increased fatness in these steers were noted for backfat and marbling score. These differences were not evident for limit fed cattle. Data in the literature does not support the concept that particle size of corn will influence carcass fatness of steers.

Fecal starch often is used as an indicator of starch utilization in diets (Zinn, 1992). Tables 13 and 14 contain fecal characteristics of ADLIB and LIM steers respectively. In period 1, fecal starch of ADLIB steers increased linearly (P = .03) with increasing PS. However, fecal starch content tended to respond quadratically in period 2 and overall (P = .18 and P = .08, respectively) with higher starch content of feces of steers fed coarsely rolled corn. Lower fecal starch for steers fed fine rolled corn probably reflects a greater extent of ruminal fermentation of the fine particles. Mastication may have been greater for the whole than the coarsely rolled grain during the second half of the feeding period and may have altered concentration of starch in fecal dry matter.

Chewing has limited effect on mechanically processed corn (Ewing and Johnson, 1987). Hence, the mean particle size of corn reaching the rumen of steers may have been smaller or of a more optimum distribution for whole than coarsely rolled corn. In LIM steers, fecal starch concentration increased linearly with particle size in period 1(P = .07), period 2 (P = .09), and overall (P = .03). Perhaps limit feeding in period 1 increased rate of feed consumption to the point that mastication of whole corn was reduced. If this eating pattern continued throughout the entire finishing period, it would explain why fecal starch concentrations were higher for whole corn for the LIM steers.

Purine content of feces may reflect microbial activity in the large intestine (Zinn and Owens, 1986). One would expect greater microbial proliferation when more starch is available to ferment in the large intestine. Fecal purine concentrations did not differ in period 1 for ADLIB steers. In period 2, fecal purine concentration tended to be higher for steers fed finely rolled corn. Although greater ruminal starch digestion would be expected to increase the quantity of microbial matter flowing to the small intestine (Sniffen et al., 1992), nucleic acids in those microbes should be digested by pancreatic ribonuclease and purines should be absorbed and not appear in the feces. The mechanism for higher microbial growth in the large intestine with finely rolled corn is not apparent. Starch reaching the large intestine may have been more easily digested from finely rolled than less processed corn. This could explain greater large intestinal fermentation and higher purine concentrations of steers fed finely rolled corn in this study.

Protein content of the feces tended to be highest (quadratic response) for coarsely rolled grain for ADLIB steers both in period 1 ($P = .06$) and over the total trial ($P = .08$). In period 2, fecal protein content tended ($P = .11$) to respond linearly, increasing with decreasing particle size. LIM steers showed no differences in fecal protein in period 1 and over the total trial. But in period 2, decreasing particle size tended ($P = .09$) to increase concentration of protein in feces. No data were found in the literature that has studied the relationship between fecal protein or fecal purines and particle size of grain in the diet. An elevated concentration of crude protein in feces might reflect large intestinal microbial activity. Alternatively, a lower fecal pH may hold more ammonia in large intestinal digesta and increase crude protein content of feces. Differences in fecal protein may also be expected if DMI is greatly different or with diets that differ in digestibility. However, these explanations cannot adequately account for the differences we observed in this trial. Because fecal protein may originate from dietary, metabolic or microbial sources, it is difficult to draw meaningful conclusions concerning the relationship between fecal protein and corn PS.

Experiment 2. Intakes, fecal measurements, and digestibilities are summarized in Table 15. Particle size did not significantly alter total tract digestibilities (OM or starch) or fecal concentrations of starch, protein or purine. Similarly, Turgeon et al. (1983) found no difference in total tract digestion of cracked vs whole corn diets; however, they noted that total tract starch digestibility was increased by cracking the grain. Murphy et al. (1994) reported that, although digestibility of OM was lower for rolled than whole corn, rolling the corn increased total tract starch digestion. Digestibilities of OM and starch generally have been lower for whole than processed corn diets (Galyean et al., 1979; Goetsch et al., 1986; Burghardi et al., 1990).

Ruminal measurements also are summarized in Table 15. In contrast with experiment 1, DMI tended to respond quadratically ($P = .08$) being lowest for coarsely rolled corn. Murphy et al. (1994) reported that DMI was higher for whole than rolled corn. Ruminal pH for steers fed whole corn changed very little over time as compared with steers fed rolled corn diets. For steers fed whole corn, ruminal pH remained above 6.0; in contrast, pH of steers fed rolled corn dropped during the 12 h sampling period. Ruminal pH tended ($P = .06$) to respond linearly at feeding (or 24 h post-feeding) to particle size with finer particles surprisingly having the highest pH. However, by 4 and 12 h post-feeding, pH definitely was lower for steers fed the smaller particle sizes. This is similar to results of Goetsch et al. (1986) who found that ruminal pH was lower for ground than whole corn diets at 2 and 6 h post-feeding. Similar results were reported by Murphy et al. (1994) and Shuey et al. (1994). Sharp et al. (1982) found no difference in pH due to corn PS; however, they limit fed small meals each hour.

The large fluctuations over time in ruminal pH by steers given ad libitum access to feed is surprising in view of the fact that they could nibble their diets throughout the day. Perhaps the stimulation of fresh feed being provided or past experience caused these animals to consume feed rapidly when it was added. Results of studies with steers adapted to the feedlot suggest that most animals consume on average over 13 times in a day (Laudert, 1995) although some 10 to 15% of the animals may not consume any feed during a 24 h period (Owens and Ferrel, 1983). Consequently, the degree of pH fluctuation in steers adapted to the feedlot may be less extreme than observed in steers in this trial.

Total ruminal VFA concentration inversely reflected ruminal pH. Total VFA for whole and coarsely rolled corn were similar at feeding time, but total VFA concentration in the rumen of steers fed finely rolled corn tended to be lower (linear effect of particle size, $P = .07$). By four hours post-feeding, total VFA concentrations had become nearly equal for all particle sizes, but 12 h post-feeding, total VFA for rolled grains were higher than for whole corn (linear effect, $P < .01$) with ranking being exactly opposite that observed at feeding time. VFA concentrations were higher with rolled than whole corn at 2, 3, 4, 6 and 9 h post-feeding in a study by Murphy et al. (1994). However, Sharp et al. (1982) and Shuey et al. (1994) detected no differences in total VFA concentration when comparing whole with rolled corn.

Acetate, propionate and lactate (D and L) concentrations were not altered by particle size at feeding time although butyrate tended to be highest for whole corn (linear effect, $P = .06$) . Propionate proportion was greater, but butyrate concentration remained lower, with smaller particle sizes at 4 h after feeding. The proportion of acetate was not affected by particle size at feeding or 4 h after feeding. Hence, with the change in propionate, the acetate to propionate ratio at 4 h post-feeding increased as PS increased ($P = .02$). The L and D-lactate concentrations at 4 h post-feeding tended ($P = .10$) to be greater in steers fed smaller particle size grain.

At 12 h after feeding, finer particle sizes resulted in higher propionate but lower acetate and butyrate proportions (linear effect, $P < .01$); the acetate to propionate ratio also was lower with the finer particle sizes. Lactate concentration was not altered by particle size although values tended to be highest for finely rolled corn at 4 h after feeding. Shuey et al. (1994) detected no effect of grain processing on VFA proportions although they did observe that lactate concentrations were higher at 3 and 6 h post-feeding for steers fed rolled than for steers fed whole corn. Murphy et al. (1994) reported that the proportion of propionate was greater while acetate was less in steers fed rolled than in steers fed whole corn matching results we observed 12 h post-feeding. But, in contrast to the present study, they observed that the proportion of butyrate was greater with rolled than whole corn, precisely opposite our findings at all sampling times.

Results could be interpreted to suggest that compared with whole corn, feeding finely rolled corn reduces ruminal pH and tends to increase ruminal concentrations of lactate and total VFA of which a higher proportion is propionate all at 12 h post-feeding. This implies that the finer the particle size, the greater the rate and extent of ruminal fermentation. Higher propionate levels should enhance efficiency by reducing the methane losses associated with acetate and butyrate formation. Total tract OM and starch digestibility was increased (experiment 1) or not altered (experiment 2) by fine rolling of the grain.

Performance data (experiment 1) suggests that feed efficiency was superior for whole corn diets when cattle were given ad libitum access to feed. A decreased rate of ruminal starch digestion from the larger particle size should decrease the extent of ruminal fermentation which in turn increases the amount of starch flowing to the small intestine (Galyean et al., 1979). Post-ruminal starch digestion is critical to cattle fed whole corn. The fact that feed efficiency was best when total tract digestibility of starch and OM matter was less than maximum indicates that feed efficiency is being improved by shifting site of starch digestion from the rumen to the small intestine.

Mastication and rumination are critical to the utilization of whole corn (Teeter et al., 1980; Ewing and Johnson, 1987). Anzola (1987) found that whole corn placed in the rumen (in situ) remained virtually inert. In the small intestine, only 7.4% of the available starch disappeared from the undamaged kernel. The presence of whole kernels in the feces of feedlot cattle probably reflects inadequate chewing by individual animals (Wilson et al., 1973). However, as demonstrated in this study, higher fecal starch levels do not necessarily mean that energetic efficiency is poorer.

Limit feeding may have an effect on the utilization of whole corn. Murphy et al. (1994) reported that digestibility of OM and starch were lower when steers were fed whole corn at 1.3 than at 2.0 times maintenance. Although limit fed cattle in the present study performed satisfactorily, the maximum improvements in efficiency noted from limit feeding were greatest for finely rolled corn and were not detected with whole corn diets fed ad libitum. Additional research exploring the relationship between limit feeding benefits and grain processing is needed.

Although no acute metabolic disorders were observed in these studies, the lower pH and fluctuating pH associated with smaller particles may increase the incidence of acidosis and ailments related to acidosis such as liver abscess, laminitis and polioencephalomalacia (Brent, 1976). Acidosis may have a deleterious affect on rate and efficiency of gain and may decrease absorption of VFA for several months after a single incident of acidosis. Severe liver abscesses negatively impact both rate and efficiency of gain (Shin et al., 1988; Brink et al., 1990). Hence, some of the efficiency advantage noted with feeding of whole corn may be the result of a reduction in the incidence of metabolic problems.

Implications

Although starch from corn grain was less extensively digested when it was fed whole rather than rolled, feed efficiency tended to be better for whole than rolled corn. Ruminal pH and VFA concentrations remained much more stable with time after fresh feed was provided in steers fed their corn whole. Lactate production also tended to be highest with finely rolled corn. An increased extent of ruminal fermentation, as reflected by higher total VFA concentrations and a higher proportion of propionate, did not maximize feed efficiency. This supports the concept that efficiency can be improved by substituting post-ruminal for ruminal digestion of starch. However, limiting feed intake reduced or eliminated the effect of particle size on feed efficiency. For younger cattle that chew their feed more thoroughly given ad libitum access to concentrate diets, rolling corn prior to feeding will not enhance feed efficiency and, due to the cost of processing, will reduce economic efficiency.

Table 7. Implant and days on feed data for blocks.

Block	July	September	November
Date placed on feed	July 14, 1994	Sept. 15, 1994	Nov. 15, 1994
First implant day (Synovex)	42	0	0
Second implant day (Revalor)	131	93	82
Slaughter date	Feb. 7, 1995	March 7, 1995	May 9, 1995
Total days on feed	208	173	175
Days after final implant	77	80	93

Table 8. Diet and calculated nutrient composition (% of DM).

Ingredient	% of diet DM
Corn, dry	82.05
Cottonseed hulls	8.00
Soybean meal	4.00
Cottonseed meal	4.00
Limestone	1.00
Urea	.60
Salt	.30
Manganous oxide	.004
Copper sulfate	.001
Zinc sulfate	.002
Vitamin A-30	.01
Rumensin-80	.017
Tylan-40	.013
Calculated nutrient content, DM basis[a,b,c]	
NEm, Mcal/kg[a]	2.09
NEg, Mcal/kg[a]	1.32
Crude protein, %[b]	13.4
Potassium, % [c]	.57
Calcium, % [c]	.44
Phosphorus, % [c]	.32
Magnesium, % [c]	.16
Cobalt, ppm	.01
Copper, ppm	8.5
Iron, ppm	51.5
Manganese, ppm	44.0
Selenium, ppm	.17
Zinc, ppm	34.9

[a] NEm and NEg based on values for ingredients from NRC (1984).
[b] Crude protein was based on Kjeldahl analysis of individual feeds.
[c] Analyzed by Servi-Tech Laboratories, Dodge City, KS.

Table 9. Feedlot performance and the particle size (PS) by limit feeding (LIM) interaction for steers fed different corn particle sizes ad libitum: linear (L) or quadratic (Q) effects.

Item	Fine 1,550 µm	Coarse 3,100 µm	Whole 5,700 µm	SEM	*P* =	PS X LIM Interaction, *P*=
Steers, n	24	24	24			
Weight, kg						
Initial	244	249	246	1.6	L, .47	
Final, live[a]	499	533	517	7.2	Q, .01	.44
Final, carcass[b]	499	533	514	8.3	Q, .02	.31
DMI, kg/d						
First half	7.5	8.3	7.2	.34	Q, .07	.57
Second half	9.1	9.1	8.5	.39	Q, .21	.78
Total	8.3	8.8	7.9	.32	Q, .10	.67
ADG, kg						
First half	1.51	1.68	1.62	.06	Q, .13	.06
Second half	1.22	1.38	1.22	.08	Q, .14	.07
Total	3.02	3.37	3.18	.05	Q, .04	.26
Feed:Gain						
First half	4.94	4.96	4.36	.25	L, .11	.30
Second half	7.38	6.78	6.87	.41	Q, .44	.27
Total	5.93	5.68	5.32	.23	L, .09	.64
Calculated diet energy						
ME, Mcal/kg	2.98	3.10	3.20	.08	L, .09	.63
NEg, Mcal/kg	1.28	1.35	1.42	.09	L, .07	.64

[a]Full weight minus 4% for gut fill.

[b]Calculated using carcass weight and mean dressing percentage.

Table 10. Feedlot performance for steers limit (83% of ad libitum) fed different corn particle sizes for the first half of the feeding period: linear (L) or quadratic (Q) effects.

Item	Fine 1,550 µm	Coarse 3,100 µm	Whole 5,700 µm	SEM	*P* =
Steers, n	24	24	24		
Weight, kg					
Initial	243	244	247	1.6	L, .10
Final, live[a]	503	513	503	7.2	Q, .29
Final, carcass[b]	498	503	499	8.3	Q, .69
DMI, kg/d					
First half	6.3	6.7	6.2	.34	Q, .32
Second half	9.1	9.1	8.8	.39	L, .61
Total	7.7	7.9	7.5	.32	Q, .50
ADG, kg					
First half	1.36	1.42	1.21	.06	L, .09
Second half	1.36	1.37	1.51	.08	L, .20
Total	1.38	1.40	1.37	.05	Q, .70
Feed:Gain					
First half	4.66	4.75	5.08	.25	L, .25
Second half	6.17	6.48	5.76	.41	Q, .38
Second half	7.38	6.78	6.87	.41	Q, .44
Calculated diet energy					
ME, Mcal/kg	3.14	3.11	3.20	.08	L, .52
NEg, Mcal/kg	1.37	1.37	1.41	.09	L, .60

[a]Weight minus 4% for gut fill.

[b]Calculated using carcass weight and mean dressing percentage.

Table 11. Carcass characteristics and the particle size (PS) by limit feeding (LIM) interaction for steers fed different corn particle sizes ad libitum: linear (L) or quadratic (Q) effects.

Item	Fine 1,550 μm	Coarse 3,100 μm	Whole 5,700 μm	SEM	*P* =	PS X LIM Interaction, *P*=
Hot carcass weight, kg	317	338	326	5.2	Q, .02	.33
Dress, %	63.6	63.5	63.1	.65	L, .65	.74
Quality grade, %						
Prime	4.2	8.3	0.0	3.5	Q, .21	.84
Choice	45.8	33.3	50.0	6.1	Q, .09	.24
Select	50.0	58.3	45.8	10.5	Q, .46	.77
Standard	0.0	0.0	4.2	3.5	L, .39	.11
Yield grade	3.2	3.2	3.1	.11	L, .60	
Marbling Score[a]	408	422	410	18.2	Q, .51	.96
Backfat, cm	1.5	1.5	1.4	.08	Q, .65	.92
KPH, %	1.7	2.2	1.8	.09	Q, .003	.18
REA, cm^2	73.5	79.4	77.4	2.1	Q, .14	.38

[a]Select > 300, Choice > 400, Prime > 600.

Table 12. Carcass characteristics for steers limit (83% of ad libitum) fed different corn particle sizes for the first half of the feeding period: linear (L) or quadratic (Q) effects.

Item	Fine 1,550 μm	Coarse 3,100 μm	Whole 5,700 μm	SEM	*P* =
Hot carcass weight, kg	316	319	317	5.2	Q, .66
Dress, %	62.9	62.3	63.0	.65	Q, .45
Quality grade, %					
Prime	0.0	0.0	0.0	3.5	1.00
Choice	43.5	45.8	58.3	6.1	L, .10
Select	48.2	54.2	41.7	10.5	Q, .53
Standard	8.3	0.0	0.0	3.5	L, .16
Yield grade	3.1	3.1	3.1	.11	L, .92
Marbling Score[a]	414	430	416	18.2	Q, .51
Backfat, cm	1.4	1.5	1.4	.08	Q, .54
KPH, %	1.7	1.8	1.8	.09	L, .36
REA, cm^2	75.5	76.1	75.5	2.1	L, .89

[a]Select > 300, Choice > 400, Prime > 600.

Table 13. The effects of corn particle size on fecal characteristics and the particle size (PS) by limit feeding (LIM) interaction of steers fed ad libitum: linear (L) or quadratic (Q) effects.

Item	Fine 1,550 μm	Coarse 3,100 μm	Whole 5,700 μm	SEM	*P* =	PS X LIM Interaction, *P*=
Starch, %						
First half	16.0	22.5	23.0	1.79	L, .03	.94
Second half	17.5	24.2	17.8	3.71	Q, .18	.09
Total	16.6	23.4	20.7	2.18	Q, .08	.06
Protein, %						
First half	18.2	27.4	18.4	3.50	Q, .06	.24
Second half	21.0	19.2	19.4	.55	L, .11	.88
Total	19.3	23.3	18.9	1.73	Q, .08	.17
Purines, %						
First half	14.3	13.5	14.5	1.16	Q, .58	.93
Second half	14.2	11.8	12.5	.70	Q, .08	.07
Total	14.2	12.7	13.7	.76	Q, .19	.15

Table 14. The effects of corn particle size on fecal characteristics of for steers limit (83% of ad libitum) fed sizes for the first half of the feeding period: linear (L) or quadratic (Q) effects.

Item	Fine 1,550 μm	Coarse 3,100 μm	Whole 5,700 μm	SEM	*P* =
Starch, %					
First half	17.8	18.6	22.8	1.79	L, .07
Second half	16.8	16.3	25.9	3.71	L, .09
Total	17.5	17.6	24.6	2.18	L, .03
Protein, %					
First half	18.2	17.9	18.2	3.50	Q, .94
Second half	19.5	19.4	18.2	.55	L, .09
Total	18.8	18.5	18.1	1.73	L, .79
Purines, %					
First half	15.1	13.2	13.7	1.16	Q, .36
Second half	13.9	12.8	11.2	.70	L, .02
Total	14.7	13.0	12.5	.76	L, .09

Table 15. The effects of corn particle size on ruminal pH, VFA and Lactate and fecal nutrient content of steers: linear (L) or quadratic (Q) effects.

Item	Fine 1,550 µm	Coarse 3,100 µm	Whole 1,500 µm	SEM	*P* =
Total DMI, kg	10.7	9.4	11.2	.83	Q, .08
Fecal starch, %	18.3	18.8	18.8	1.9	L, .79
Fecal protein, %	16.8	15.6	17.6	.94	L, .39
Fecal purines, %	18.9	17.0	14.8	2.0	L, .50
OM digestibility, %	78.5	77.8	79.4	2.8	Q, .69
Starch digestibility, %	94.5	93.9	94.4	1.1	Q, .57
Pre-feeding					
pH	6.47	6.20	6.16	.14	L, .06
Acetate, %	50.2	47.7	48.2	2.29	Q .40
Propionate, %	40.3	43.5	37.3	3.07	Q, .14
Butyrate, %	9.5	8.8	14.5	2.59	Q, .06
L-lactate, mg/dl	4.17	4.58	5.33	1.22	L, .35
D-lactate, mg/dl	.58	1.83	1.92	1.31	L, .37
Acet.: prop. ratio	1.25	1.11	1.41	.16	Q, .18
Total VFA, mM	91.17	137.45	138.75	21.70	L, .07
Four h post-feeding					
% of total DMI	49.5	65.7	49.4	14.90	Q, .24
pH	5.60	5.78	6.06	.17	L, .01
Acetate, %	45.1	44.8	47.6	2.70	L, .34
Propionate, %	45.5	46.2	36.4	3.52	L, .02
Butyrate, %	9.3	9.0	15.9	2.81	L, .03
L-lactate, mg/dl	24.08	4.83	4.00	10.18	L, .10
D-lactate, mg/dl	17.08	.50	.75	8.21	L, .10
Acet.: prop. ratio	1.00	.99	1.45	.18	L, .02
Total VFA, mM	161.85	161.45	146.49	13.00	L, .24
Twelve h post-feeding					
% of total DMI	91.4	92.5	87.3	5.7	Q, .61
pH	5.42	5.67	6.20	.18	L, .0007
Acetate, %	42.4	42.1	48.4	1.61	L, .003
Propionate, %	47.7	46.4	33.7	3.46	L, .002
Butyrate, %	9.9	11.5	17.9	3.45	L, .04
L-lactate, mg/dl	4.67	4.17	4.83	.63	Q, .33
D-lactate, mg/dl	1.50	.58	2.67	1.24	Q, .24
Acet.: prop. ratio	.90	.93	1.57	.15	L, .0009
Total VFA, mM	176.82	167.76	133.79	9.42	L, .0008

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CHAPTER V

IMPACT OF PARTICLE SIZE OF HIGH MOISTURE CORN ON PERFORMANCE OF FEEDLOT STEERS

Abstract: A feeding trial and a metabolism trial were conducted to examine the effects of particle size and the distribution of particle size of high moisture corn on feedlot steer performance, carcass characteristics and ruminal fermentation. In the feeding trial, high moisture corn (70% DM) was harvested from one field and either rolled (3 different degrees of fineness) or ground prior to being ensiled in Ag Bags®. Continental-crossbred yearling steers (N = 192, 334 kg.) were allotted to four corn processing treatments and given ad libitum access to totally mixed diets for 97 d. Effects of mean particle size (PS) or standard deviation (SD) of the mean particle size, an estimate of particle size distribution, were evaluated. Treatments were fine (1280 μm, SD = 2.04), medium (1630 μm, SD = 2.15), or coarse (2120 μm, SD = 2.25) rolled grain, and corn ground (1830 μm, SD = 2.36) through a tub grinder. Over the total trial, ADG increased as particle size increased ($P < .05$) but DMI and feed efficiency were not significantly altered by PS. The percentage of carcasses grading choice also tended ($P = .06$) to increase with increasing PS but other carcass traits were not affected by PS. PS had no effect on fecal concentration of nutrients or digestibility. As the distribution in particle size widened, gain was increased linearly ($P < .01$) and feed to gain ratio improved linearly ($P < .01$). Kidney-heart and pelvic fat also tended ($P = .06$) to increase as distribution in particle size increased. Total tract starch digestibility and purine content of feces decreased ($P < .01$) as SD increased. In the metabolism trial, four ruminally cannulated steers were placed with intact steers in feedlot pens to examine the effects of corn particle size and its distribution on ruminal fermentation in a 4 by 4 Latin square. At 17 h post-feeding, L-lactate concentration was increased ($P < .01$) and D-lactate tended to increase ($P = .11$) as particle size decreased but ruminal pH and VFA profiles did not differ with particle size.

However, a broader distribution in particle size resulted in a lower proportions of ruminal acetate ($P < .02$) and more propionate ($P < .01$) at 4 h after fresh feed was provided. Lactate, total VFA concentrations or pH were not altered by extent of distribution in particle size. Results could be interpreted to suggest that a broader distribution in particle size of the grain can enhance rate and efficiency of gain, perhaps due to stabilization of fermentation rate in the rumen or to increased flushing of starch particles to the small intestine for digestion.

(Key Words: High moisture corn, Particle size, Feedlot, Fermentation)

Introduction

To maximize diet digestibility, grains should be processed as thoroughly as possible. However, to maximize feed intake and feed efficiency, diet palatability must be maintained and acidosis must be avoided. This means that maximum diet digestibility may not maximize feed efficiency (Owens et al., 1986; Secrist et al., 1995a). Grains are processed to increase starch digestibility, and thereby enhance rate and efficiency of gain of feedlot cattle (Van Koevering et al., 1994; Owens et al., 1995; Secrist et al., 1995b). Compared with dry corn, ensiled high moisture corn is digested rapidly due to the large surface area exposed for digestion and partial solubilization of the protein which increases starch solubility in the rumen (Theurer, 1986). The smaller the particle size of high moisture corn, the more rapid the ruminal fermentation of starch and organic matter (Galyean et a., 1981). The objective of this experiment was to examine the effects of pre-ensiling processing of high moisture corn grain (rolling to three different particle sizes vs hammer milling through a tub grinder) on the performance, carcass characteristics and the ruminal environment of growing steers.

Materials and Methods

Feeding trial. Corn was harvested from a single corn variety in one field near Guymon, OK on September 9, 1995 when the corn grain contained approximately 30% moisture. This grain was transported to the OK Panhandle State University feedlot research facilities at Goodwell, OK and rolled through a commercial, two tiered roller mill (2 roller pairs) provided by Automatic Equip. Mfg., Pender, NE. Rolls were set to process the corn to three different extents (fine, medium and coarse) and the rolled corn was ensiled in plastic bags (Ag Bag®). The remaining corn was ground in a commercial tub grinder and transported to Panhandle State University where it was ensiled in the same manner. All grain was stored until feeding began on January 21, 1995 (d 0). Mean particle size and particle distribution of treatments are contained in Table 16 and illustrated graphically in Figure 1.

Continental crossbred yearling steers (N = 192) were received at Panhandle State University on January 6, 1995 (d -13) after being transported from a local feedyard (25 km). Upon arrival the steers were individually weighed, tagged, vaccinated with a 4-way respiratory and 7-way clostridial vaccine, injected with Ivomec-F® (MSD Ag Vet Merck. Division of Merck & Co., Inc. Rahway, NJ) and implanted with Synovex-S® (200 mg progesterone, 20 mg estradiol benzoate; Syntex, West Des Moines, IA). The cattle were reimplanted with Revalor-S® (120 mg trenbolone acetate, 24 mg estradiol; Hoechst-Roussel Agri-Vet, Somerville, NJ) on d 39. The cattle were stratified by weight into four weight blocks and assigned randomly to one of four corn particle size (PS) treatments. The steers were housed in 16 (12 head/pen, 4 pens per treatment) outside pens (39 X 30 m) equipped with cement fenceline feedbunks and automatic waterers. Pen was the experimental unit.

The isocaloric and isonitrogenous high moisture corn diets (Table 16) diets were provided to steers for ad libitum consumption with fresh feed being delivered once daily (4 p.m.). The supplemental ingredients (alfalfa hay and protein supplement) were sampled each month and analyzed at a commercial laboratory for DM, crude protein, calcium, phosphorous and potassium. Grain was sampled weekly. The diets differed only in the extent of corn processing prior to ensiling. The starting diet, consisting of 50% alfalfa hay and 50% steam-flaked corn, was fed from d -13 to d 0; then cattle were gradually adapted to their respective diets by decreasing the roughage level to 8% over a 21-day period. Cattle had ad libitum access to their diets through d 97 when the available corn had all been fed. Because the cattle had not reached slaughter grade at that time, final live weights were taken at that time and thereafter, from d 98 until slaughter, d 129 and 130, ground high moisture corn was transported from a commercial feedlot and fed to all cattle.

Steers were weighed following transport to the feedlot (d -13) and on d 0, 14, 39, 69, 97 and 124. A 4% pencil-shrink was applied to live weights before ADG calculation. Because the corn was depleted before the cattle reached finish weights, weights taken on d 97 served as the final live weights for the trial. ADG for the first 39 days of the feeding period was calculated as the slope of the regression line through the corresponding (d 0, 14 and 39) interim weights. ADG for the second half of the feeding trial (d 39 to 97) was calculated in the same manner using the corresponding (d 39, 69 and 97) interim weights. ADG for the total period was calculated as the slope of the regression line through weights obtained on d 0, 14, 39, 69 and 97. Feed intake was expressed as the mean DMI divided by the number of animals in the pen. Feed efficiency was expressed as average daily DMI (pen total prorated among all animals in the pen) divided by mean ADG.

Corn samples were taken each week and particle size determined by a commercial laboratory by the procedure of Ensor et al., 1970. Cottonseed hull-based pellets containing chromic oxide were fed from d 59 through d 69 to provide each animal with 10 g chromic oxide/d. Fecal samples were collected from steers in each pen on d 67 (p.m.), 68 (a.m. and p.m.) and 69 (a.m.). Fecal samples were composited across time, dried at 100°C for 48 h, ground through a 2 mm screen and analyzed for starch (MacRae and

Armstrong, 1968), protein (AOAC, 1990), nucleic acids (purine; Zinn and Owens, 1986), and chromium concentrations (Hill and Anderson, 1958). Total tract OM and starch digestibilities were calculated.

All animals were slaughtered at a commercial packing facility (Excel Corporation, Dodge City, KS) on d 129 and 130. Carcass data were collected following a 48 hr chill. The following measurements were obtained: 1) longissimus area, measured by direct grid reading of the longissimus at the 12th rib; 2) subcutaneous fat over the longissimus at the 12th rib taken at a location 3/4 the lateral length from the chine bone end; 3) kidney, pelvic and heart fat (KPH) as a percentage of carcass weight, and 4) marbling score (USDA, 1965). Yield grades were calculated using these values.

This study was constructed as a randomized complete block design. Animals were blocked based on weight on day -13. The data were analyzed by general linear model procedures of SAS (1988) with pen as the experimental unit without subsampling. Model effects include weight block and mean particle size (or particle size SD). Linear and quadratic effects were separated by orthogonal contrasts for the unequal spacing of particle size. In addition, data were analyzed identically using standard deviation of particle size as the independent numeric variable. Because different processing methods were employed (rolling and grinding) and grinding resulted in a broader distribution in particle sizes than rolling, we considered that it was important to test effects both of particle size standard deviation as well as in mean particle size. These effects are confounded and cannot be separated. Results of both analyses appear in the text and will be discussed separately.

Metabolism trial. Four yearling beef steers (295 kg) fitted with permanent ruminal cannulae were transported to Panhandle State University (Feb. 17, 1995) and adapted to the finishing diet during an 11-d period. On February 28, 1995, the steers were each moved into pens occupied by the 12 intact steers that were part of experiment 1. The cannulated steers were group fed with other steers in an attempt to match intake patterns and behavior. Steers were rotated among pens so that each of the four particle size treatments (fine rolled, medium rolled, coarse rolled and ground corn) could be tested in the 4 X 4 Latin square. All diets were available ad libitum with fresh feed being provided at 4:00 p.m. Sampling began on March 8, 1995 and continued for 28 days with a 6 d adaptation period between sampling days. Samples were taken one hour before feeding (1400), and at 4 (1900) and 17 (0800) hours post-feeding. Cannulated steers were removed from the pen for sampling but returned immediately after being sampled.

Ruminal samples were strained through 4 layers of cheese cloth and pH was measured immediately. A 5 mL aliquot was mixed with 250 mg of metaphosphoric acid (Erwin et al., 1961) to conserve it for VFA analysis. Volatile fatty acid concentrations were determined by gas chromatography (Harmon et al., 1985). An additional 5 mL aliquot was mixed with 5-mL of 20% trichloroacetic acid solution to conserve it for lactate analysis. Lactate concentration (both D and L isomers) was determined spectrophotometrically (COBAS MIRA, Chemistry Systems, St. Louis, Missouri).

The study was analyzed by general linear model procedures of SAS (1988). The model included steer, sampling period and either mean particle size or standard deviation of mean particle size. Linear and quadratic effects were examined by orthogonal contrasts among the unequally spaced numeric variables as described for the feeding trial.

Results and Discussion

Feeding trial. Feedlot performance is summarized in Tables 17 (with standard deviation serving as the independent variable) and 18 (with mean particle size serving as the independent variable). Because relationships between performance and particle size distribution were strong, those will be discussed first.

ADG tended ($P = .10$) to respond quadratically with particle size distribution during the first 39 days on feed. Steers fed the medium (SD = 2.15 μm) and coarsely rolled (SD = 2.25 μm) corn tended to have higher gain with ground (SD = 2.36 μm) corn being numerically lowest. Differences in feed intake probably are responsible for these differences although those differences were not significant (*P* = .15). Feed efficiency during the first 39 days favored the coarsely rolled corn which tended to respond quadratically (*P* = .18). These data suggest that rolled corn in general (lower SD) tended to increase rate and efficiency of gain early in the feeding trial.

ADG, DMI and feed efficiency from d 39 to 97 all tended to responded linearly to SD (P= .01; P = .16; P = .01), with ADG and DMI tending to increase and efficiency improving as SD increased. Results from period 1 tended to dilute differences noted in the later portion of the feeding period so that only trends were noted in total trial performance for ADG and DMI tending to increase (*P* = .10; *P* = .15) as SD increased. Davis (1980) reported that DMI and ADG were higher when high moisture corn was rolled rather than ground. Because SD normally is lower for rolled than ground grain, his results are opposite those observed here although particle sizes were not specified. However, similar to the present study, Van Koevering et al. (1994) observed that DMI was greater with rolled than with ground high moisture corn, although both forms produced similar rates and efficiencies of gain.

Carcass data are summarized in table 19. KPH tended (*P* = .06) to increase as SD increased although other carcass measurements do not reflect an increased fatness at other sites. Variation in particle size tended to have a quadratic effect (*P* = .10) on the percentage of carcasses grading choice, being highest for steers fed the coarsely rolled corn, but other carcass measurements were not altered by particle size distribution.

Fecal concentration of nutrients and total tract digestibilities are summarized in Table 21. Although OM digestibility and fecal protein content were not affected by corn processing, starch content of feces increased (P= .01) and starch digestibility decreased (P =.01) as variation in particle size increased. Fecal starch concentration can be used as an indication of starch utilization (Zinn, 1992). Purine concentration in feces tended to decrease linearly (*P* = .06, linear) as SD decreased. Purine concentration may reflect the extensiveness of microbial fermentation in the large intestine (Zinn and Owens, 1986). Although one might expect fecal purines to parallel fecal starch, these changed in opposite directions. Perhaps the starch reaching the large intestine from finely ground grain is more accessible for microbial attack. Whole corn was present both in the feed and feces of steers fed the ground (SD=2.36) high moisture corn.

The data on starch digestibility could be interpreted to suggest that corn processed to produce a less variable (and finer) product will maximize digestibility of the starch in the diet. However, at the time of the feeding trial that fecal samples were taken (d 70), the cattle on the treatment with the lowest starch digestibility (ground; SD = 2.36) had the best rates and efficiencies of gain. Starch digestion may have been shifted from the rumen to the small intestine which could have increased energetic efficiency (Owens et al., 1986). Alternatively, cattle fed the more highly processed corn may have been experiencing subclinical acidosis and more day-to-day variation in feed intake. Indeed, mean feed intake tended to be lower for steers fed finely rolled corn. Though liver data were not collected, severe liver damage associated with acidosis has been shown to depress animal performance (Shin et al., 1988; Brink et al., 1990).

Utilizing mean particle size as the numeric variable in essence serves to switch the numeric order of comparison so that coarse rolled corn becomes greater than ground corn. Such analysis ignores differences in particle size distribution although the two factors are confounded. Feedlot performance is summarized in Table 18. ADG and DMI were not altered by PS during the first 39 days on feed. However, feed efficiency tended ($P = .13$) to respond quadratically with ground corn (1,830 μm) producing the poorest feed efficiency.

ADG from d 39 to 97 tended ($P = .10$, quadratic) to be highest for ground (1,830 μ m) and DMI tended ($P = .20$) to be least for finely rolled (1,280 μm) corn. Feed efficiency, responding quadratically ($P = .15$) tended to favor ground (1,830 μm) corn.

Overall, ADG and DMI tended to increase linearly as particle size increased although feed efficiency was not altered.

Carcass data for steers fed different PS are summarized in Table 20. Cattle fed coarsely rolled corn (2,120 μm) tended ($P = .11$, linear) to be heavier and tended ($P = .06$, linear) to have a higher percentage of carcasses grade choice. Other carcass data were not altered by PS. For fecal concentration of nutrients and digestibility, summarized in Table 22, linear and quadratic effects ($P = .15$) of particle size were not significant.

Results seem most easily explained by differences in corn particle size distribution. Particles of smaller size and greater surface area are fermented more rapidly in the rumen and leave less residue for digestion in the small intestine even though the residual starch may be more digestible in the small intestine. Slowing the rate of rumen fermentation by providing larger particles also should help maintain a higher ruminal pH and decrease the potential for acidosis. Feed intake may be greater early in the feeding period for coarsely rolled than ground grain (Davis, 1980; Van Koevering et al., 1994) at a time when diet palatability is most important.

Mader et al. (1991) found that feeding high moisture corn whole or mixed with rolled corn improved rate and efficiency of gain as compared with rolled or ground high moisture corn fed alone. When compared with ground high moisture corn, rolled corn produced better feed efficiency, although the particle size distribution was not reported. One would presume that the particle size distribution of the digesta reaching the rumen would be considerably greater for the whole or mixed diets than for the rolled or ground fed alone due to the presence of coarser, less masticated particles (Ewing and Johnson, 1987). In contrast, Stock et al. (1991) fed rolled (31% whole kernels) or whole high moisture corn to feedlot steers. Although rolling did not affect DMI, ADG and feed efficiency, both were improved beyond values obtained for steers fed high moisture corn that was not rolled. Mastication of the whole high moisture corn, especially when drier, may fail to expose an adequate surface area for either ruminal or small intestinal digestion.

Mixing grain types and(or) processing methods would be expected to have similar effects i.e., attenuating fermentation, avoiding metabolic disorders, and enhancing flow of starch to the lower GI tract, as an increase in particle size within a grain type. Feed efficiency has been improved in some trials where diets have consisted of several types of grain or several different processing methods (Lee et al., 1982: Sindt et al., 1987: Stock et al., 1987; Bock et al., 1991).

Metabolism trial. Ruminal digestion parameters are summarized in tables 23 (analyzed by SD) and 24 (analyzed by PS). Particle size distribution did not significantly alter ruminal pH. Ruminal pH was lowest for all treatments 4 h post-feeding followed by a rebound at 17 h post-feeding. Neither total VFA concentration, individual VFA proportions or lactate concentration were altered by SD one h prior to (or 23 h after) feeding. However, at 4 h post-feeding, acetate concentration decreased (P =.02) and propionate concentration increased (P =.01) as particle distribution increased; this resulted in a lower acetate to propionate ratio. Finer corn particles may have been more rapidly digested than larger particles resulting in an earlier propionate concentration peak for the ground (SD=2.36) corn. The higher propionate level may partly explain the observed advantage in feed efficiency for steers fed ground (SD=2.36) high moisture corn. However, VFA concentration from finely processed high moisture corn may have simply peaked earlier than coarser grain; before ruminal sampling at 4 h after fresh feed was provided. Also, feed intake during the first four hours after feeding was not recorded. Social interactions as well as diet composition may have altered feeding patterns and increased variability in ruminal measurements. Similar to these results, Stock et al. (1987) reported that feeding a mixture of high moisture and dry rolled corn, which, in essence, should increase variation in particle size, resulted in an increased ruminal and total tract digestibility of starch as compared with either grain form fed alone. Perhaps mixing grain forms may have an associative effect and a complementary fermentation pattern which increases starch utilization. Lactate concentrations did not differ at 4 h post-feeding. At

17 h post-feeding, total VFA concentration and individual VFA proportions did not differ; however, L-lactate concentration was increased (P =.01) and D-lactate concentration tended (*P* =.11) to increase as particle size distribution and mean particle size decreased. This finding is similar to that of Mendoza et al. (1991) when they combined rolled high moisture corn with dry rolled milo; ruminal lactate concentration tended to be lower with mixed grain diets and, as suggested previously, mixtures of grains should be similar to increasing the particle size distribution. Relative starch digestion rates for milo and high moisture corn should be similar to the wide distribution of particles sizes with ground (SD=2.36) high moisture corn.

Utilizing the mean particle size as the independent variable resulted in no major alterations in data interpretation. The lower pH and increased propionate concentration observed with coarsely rolled high moisture corn at 4 h post-feeding was not expected. Maximal rumen fermentation may have taken place prior to sampling at 4 h post-feeding for the finer (fine and medium) rolled high moisture corn. As discussed earlier, differences in rate of feed intake by animals that are fed together in a pen also may have contributed to these unexpected results. Pen feeding does not provide a static environment needed to detect small differences in rumen fermentation, but feedlot cattle are not individually fed and group behavior, as it alters feeding rate and frequency may alter ruminal fermentation and should be considered. Multiple observations, either in the form of a repeated Latin square or preferably a replicated Latin square (requiring additional animals) might have helped remove the variability associated with pen feeding. Because little information has been published examining the effects of particle size of high moisture corn on ruminal fermentation, comparison of results with other studies is impossible.

Implications

Both the mean and the distribution in particle size of high moisture corn may alter feed intake and, rate and efficiency of gain by feedlot steers. During adaptation to high concentrate finishing diets, larger particle size grains increased feed intake and rate of gain. Later in the feeding period, the a wider distribution in particle sizes increased feed intake and rate and efficiency of gain. Although finer particles are more extensively digested, larger particles attenuate fermentation, which may help avoid metabolic disorders and avoid anorexia, and may provide additional starch for digestion in the small intestine. Increasing the particle size distribution in the diet, achieved either by altering the processing method, by mixing grain processed by various methods, or by adding complementary grains together, may enhance feed efficiency. Compared with rolled high moisture corn, coarsely ground high moisture corn provided a wider distribution in particle size which attenuated rate of fermentation.

Table 16. Mean geometric diameter, standard deviation and corn particle size distribution of fine, medium and coarse rolled and ground HM corn

Item	Fine	Medium	Coarse	Ground
Geometric mean diameter, µm	1,280	1,630	2,120	1,830
Particle standard deviation	2.04	2.15	2.25	2.36
Screen size, µm	Fraction of total weight, %			
4,750	0.10	2.58	10.08	9.04
3,350	4.55	12.03	24.23	19.50
2,360	18.24	25.14	23.32	19.50
1,700	20.95	19.32	13.83	14.19
1,180	15.39	11.51	7.89	9.48
850	10.62	7.71	5.37	7.00
600	8.46	6.37	4.35	5.82
425	15.70	10.11	4.72	6.71
300	4.75	3.78	4.04	5.90
212	0.72	0.76	1.21	1.09
150	0.30	0.33	0.56	0.57
106	0.15	0.23	0.28	0.32
75	0.08	0.13	0.14	0.15
53	0.00	0.03	0.00	0.05
Pan	0.00	0.00	0.00	0.00

Figure 1. Distribution particle sizes for fine, medium and coarse rolled and ground HM corn.

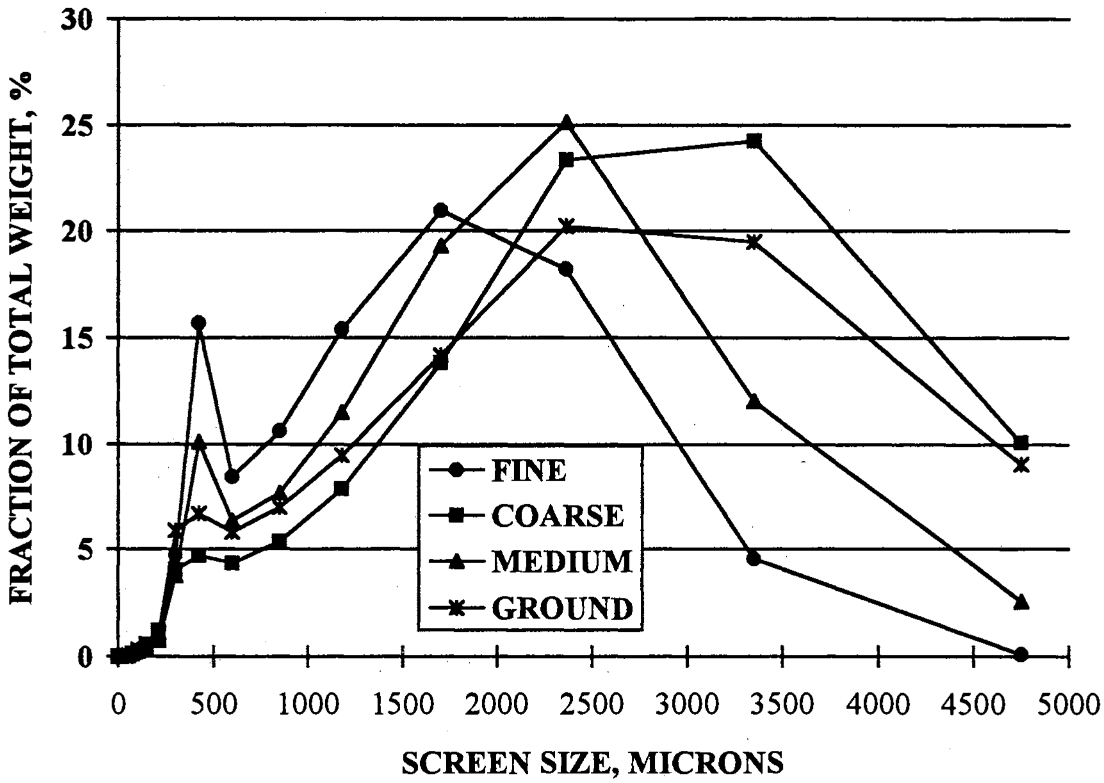

Table 17. Diet and calculated nutrient composition (% of DM).

Ingredient	% of diet DM
Corn grain, high moisture	86.10
Alfalfa hay, chopped	8.00
Soybean meal	2.00
Cottonseed meal	2.00
Limestone	.95
Urea	.60
Salt	.30
Manganous oxide	.004
Copper sulfate	.001
Zinc sulfate	.002
Vitamin A-30	.011
Rumensin-80	.017
Tylan-40	.012
Calculated nutrient content, DM basis[a,b,c]	
NEm, Mcal/kg[a]	2.12
NEg, Mcal/kg[a]	1.37
Crude protein, % [b,c]	12.6
Potassium, % [c]	.70
Calcium, % [c]	.60
Phosphorus, % [c]	..34
Magnesium, % [c]	.14
Cobalt, ppm	.11
Copper, ppm	7.9
Iron, ppm	101.2
Manganese, ppm	40.2
Selenium, ppm	.16
Zinc, ppm	29.8

[a] NEm and NEg based on values for ingredients from NRC (1984).
[b] Crude protein was based on Kjeldahl analysis of individual feeds.
[c] Analyzed by Servi-Tech Laboratories, Dodge City, KS.

Table 18. Feedlot performance for steers fed rolled (fine, medium or coarse) or rolled high moisture corn: Linear (L) or quadratic (Q) effects. Particle size standard deviation was used as the independent variable.

Item	Fine 2.04	Medium 2.15	Coarse 2.25	Ground 2.36	SEM	*P* =
Live weight, kg[a]						
Start	334	333	334	335	2.4	L, .98
Day 129	567	564	571	570	3.8	L, .33
ADG, kg						
Day 0 to 39	1.85	1.91	1.95	1.72	.08	Q, .10
Day 39 to 97	1.75	1.83	1.87	1.99	.05	L, .005
Day 0 to 97	1.82	1.88	1.94	1.90	.04	L, .10
DMI, kg/d						
Day 0 to 39	7.6	7.9	7.8	7.7	.14	Q, .15
Day 39 to 97	9.4	9.8	9.8	9.9	.25	L, .16
Day 0 to 97	8.7	9.0	9.0	9.0	.19	L, .15
Feed: Gain						
Day 0 to 39	4.13	4.18	4.02	4.53	.16	Q, .18
Day 39 to 97	5.39	5.36	5.27	5.02	.08	L, .007
Day 0 to 97	4.78	4.80	4.67	4.77	.08	Q, .63

[a]Live-weight with a 4% shrink.

Table 19. Feedlot performance for steers fed rolled (fine, medium or coarse) or rolled high moisture corn: Linear (L) or quadratic (Q) effects. Mean particle size used as the independent variable.

Item	Fine 1,280 μm	Medium 1,630 μm	Ground 1,830 μm	Coarse 2,120 μm	SEM	*P* =
Live weight, kg[a]						
Start	334	333	335	334	2.4	L, .98
Day 129	567	564	570	571	3.8	L, .11
ADG, kg						
Day 0 to 39	1.85	1.91	1.72	1.95	.08	Q, .32
Day 39 to 97	1.75	1.83	1.99	1.87	.05	Q, .10
Day 0 to 97	1.82	1.88	1.90	1.94	.04	L, .05
DMI, kg/d						
Day 0 to 39	7.6	7.9	7.7	7.8	.14	Q, .50
Day 39 to 97	9.4	9.8	9.9	9.8	.25	L, .20
Day 0 to 97	8.7	9.0	9.0	9.0	.19	L, .15
Feed: Gain						
Day 0 to 39	4.13	4.18	4.53	4.02	.16	Q, .13
Day 39 to 97	5.39	5.36	5.02	5.27	.08	Q, .15
Day 0 to 97	4.78	4.80	4.77	4.67	.08	L, .38

[a]Live-weight with a 4% shrink.

Table 20. Carcass characteristics of steers fed rolled (fine, medium or coarse) or ground high moisture corn: Linear (L) or quadratic (Q) effects. Particle size standard deviation used as the independent variable.

Item	Fine 2.04	Medium 2.15	Coarse 2.25	Ground 2.36	SEM	*P* =
Hot weight, kg	357	358	363	361	2.4	L, .22
Dress, %	65.4	65.3	65.1	65.4	0.2	Q, .37
Marbling Score[a]	336	344	351	344	7.2	Q, .31
Choice, %	12.7	21.2	31.8	18.8	5.8	Q, .10
Select, %	63.1	61.9	49.0	54.2	10.8	L, .44
Standard, %	23.2	16.9	17.0	27.1	7.5	Q, .27
Backfat, cm	1.0	1.0	1.0	1.1	.05	Q, .59
KPH, %	1.3	1.4	1.4	1.5	.07	L, .06
Yield grade	1.9	2.0	2.0	2.0	.07	L, .92
Ribeye area, cm^2	96.1	96.1	94.2	96.1	1.1	Q, .38

[a]Select > 300, Choice > 400, Prime > 600.

Table 21. Carcass characteristics of steers fed rolled (fine, medium or coarse) or ground high moisture corn: Linear (L) or quadratic (Q) effects. Mean particle size used as the independent variable.

Item	Fine 1,278 μm	Medium 1,630 μm	Ground 1,830 μm	Coarse 2,120 μm	SEM	*P* =
Hot weight, kg	357	358	361	363	2.4	L, .11
Dress, %	65.4	65.3	65.4	65.1	0.2	L, .36
Marbling Score[a]	336	344	344	351	7.2	L, .19
Choice, %	12.7	21.2	18.8	31.8	5.8	L, .06
Select, %	63.1	61.9	54.2	49.0	10.8	L, .34
Standard, %	23.2	16.9	27.1	17.0	7.5	L, .67
Backfat, in	1.0	1.0	1.1	1.0	.0	Q, .71
KPH, %	1.3	1.4	1.5	1.4	.0	L, .28
Yield grade	1.9	2.0	2.0	2.0	.0	L, .91
Ribeye area, in^2	96.1	96.1	96.1	94.2	1.1	L, .35

[a]Select > 300, Choice > 400, Prime > 600.

Table 22. Fecal concentration of nutrients and calculated digestibilities: Linear (L) or quadratic (Q) effects. Particle size standard deviation used as the independent variable.

Item	Fine 2.04	Medium 2.15	Coarse 2.25	Ground 2.36	SEM	*P* =
Protein, %	16.91	19.16	17.07	15.19	1.7	L, .36
Purine, %	10.04	11.73	8.25	7.20	1.2	L, .06
Starch, %	5.20	5.61	8.45	11.56	.85	L, .0005
Digestibility, %						
Starch	98.8	98.9	98.1	96.9	.27	L, .0008
OM	84.1	85.5	84.8	80.8	2.1	Q, .23

Table 23. Fecal concentration of nutrients and calculated digestibilities: Linear (L) or quadratic (Q) effects. Mean particle size used as the independent variable.

Item	Fine 1,280 μm	Medium 1,630 μm	Ground 1,830 μm	Coarse 2,120 μm	SEM	*P* =
Protein, %	16.91	19.16	15.19	17.07	1.7	L, .74
Purine, %	10.04	11.73	7.20	8.25	1.2	L, .22
Starch, %	5.20	5.61	11.56	8.45	.85	Q, .19
Digestibility, %						
Starch	98.8	98.9	96.9	98.1	.27	Q, .18
OM	84.1	85.5	80.8	84.8	2.1	Q, .62

Table 24. Ruminal pH, VFA and lactate concentrations in steers fed rolled (3 particles sizes) or ground high moisture corn: Linear (L) or quadratic (Q) effects. Particle size standard deviation used as the independent variable.

Item	Fine 2.04	Medium 2.15	Coarse 2.25	Ground 2.36	SEM	*P* =
Pre-feeding						
pH	5.67	5.89	5.53	5.73	.38	L, .92
Acetate, %	47.9	46.9	46.4	49.2	1.24	Q, .12
Propionate, %	44.6	43.3	44.0	42.5	1.28	L, .29
Butyrate, %	7.5	9.8	9.6	8.3	1.20	Q, .13
L-lactate, mg/dl	7.13	7.50	7.88	8.67	.80	L, .43
D-lactate, mg/dl	16.25	16.50	17.25	16.33	1.27	L, .62
Acet.: prop. ratio	1.08	1.09	1.16	1.06	.04	L, .32
Total VFA, mM	175.66	140.56	118.28	188.94	30.97	L, .39
Four h post-feeding						
pH	5.14	5.41	5.21	5.19	.08	Q, .10
Acetate, %	50.5	46.5	45.3	45.4	1.40	L, .02
Propionate, %	41.8	44.4	45.5	46.7	1.08	L, .007
Butyrate, %	7.7	9.2	9.2	7.9	1.21	Q, .23
L-lactate, mg/dl	7.38	7.25	8.75	9.71	.93	L, .20
D-lactate, mg/dl	18.63	16.75	18.63	17.17	1.90	Q, .43
Acet.: prop. ratio	1.22	1.06	.98	1.00	.05	L, .008
Total VFA, mM	171.81	160.73	188.98	175.23	21.20	L, .51
Seventeen h post-feeding						
pH	5.36	5.78	5.32	5.58	.20	Q, .65
Acetate, %	47.7	46.1	46.7	45.6	1.39	L, .31
Propionate, %	43.7	43.8	44.2	43.7	1.60	L, .85
Butyrate, %	8.5	10.1	9.1	10.6	1.18	L, .28
L-lactate, mg/dl	9.88	7.25	8.13	7.25	.45	Q, .006
D-lactate, mg/dl	19.25	15.88	18.13	12.75	2.37	Q, .11
Acet.: prop. ratio	1.10	1.06	1.05	1.06	.06	L, .57
Total VFA, mM	155.70	184.27	178.96	193.76	20.68	Q, .33

Table 25. Ruminal pH, VFA and Lactate content of steers fed rolled (3 particles sizes) or ground high moisture corn: Linear (L) or quadratic (Q) effects. Mean particle size was used as the independent variable.

Item	Fine 1,280 µm	Medium 1,630 µm	Ground 1,830 µm	Coarse 2,120 µm	SEM	*P* =
Pre-feeding						
pH	5.67	5.89	5.73	5.53	.38	Q, .50
Acetate, %	47.9	46.9	49.2	46.4	1.24	Q, .52
Propionate, %	44.6	43.3	42.5	44.0	1.28	Q, .26
Butyrate, %	7.5	9.8	8.3	9.6	1.20	L, .32
L-lactate, mg/dl	7.13	7.50	8.67	7.88	.80	L, .26
D-lactate, mg/dl	16.25	16.50	16.33	17.25	1.27	Q, .72
Acet.: prop. ratio	1.08	1.09	1.06	1.16	.04	Q, .28
Total VFA, mM	175.66	140.56	188.94	118.28	30.97	Q, .10
Four h post-feeding						
pH	5.14	5.41	5.19	5.21	.08	Q, .11
Acetate, %	50.5	46.5	45.4	45.3	1.40	L, .02
Propionate, %	41.8	44.4	46.7	45.5	1.08	L, .02
Butyrate, %	7.7	9.2	7.9	9.2	1.21	L, .49
L-lactate, mg/dl	7.38	7.25	9.71	8.75	.93	L, .11
D-lactate, mg/dl	18.63	16.75	17.17	18.63	1.90	L, .78
Acet.: prop. ratio	1.22	1.06	1.00	.98	.05	L, .01
Total VFA, mM	171.81	160.73	175.23	188.98	21.20	L, .76
Seventeen h post-feeding						
pH	5.36	5.78	5.58	5.32	.20	Q, .02
Acetate, %	47.7	46.1	45.6	46.7	1.39	Q, .30
Propionate, %	43.7	43.8	43.7	44.2	1.60	L, .82
Butyrate, %	8.5	10.1	10.6	9.1	1.18	Q, .15
L-lactate, mg/dl	9.88	7.25	7.25	8.13	.45	L, .02
D-lactate, mg/dl	19.25	15.88	12.75	18.13	2.37	L, .15
Acet.: prop. ratio	1.10	1.06	1.06	1.05	.06	L, .63
Total VFA, mM	155.70	184.27	193.76	178.96	20.68	L, .26

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CHAPTER VI

SUMMARY OF EFFECTS OF CORN PARTICLE ON PERFORMANCE OF FEEDLOT CATTLE

Goals of Processing

One of the primary objectives of the cattle feeder is to maximize profit or minimize loss from every pen of cattle. Beyond the cost of purchasing the animals, feed constitutes the major cost involved in producing a market weight animal. Corn is processed to enhance the extent to which animals can extract energy from feed for conversion to body tissue. Most processing methods reduce the particle size of the grain in order to increase its surface area and thereby enhance the opportunity for starch digestion both by microbial enzymes in the rumen and by mammalian enzymes in the small intestine. Unfortunately, processing methods that increase extent of digestion usually increase rate of fermentation which in turn increases the probability of ruminal acidosis and metabolic disorders.

Site of starch digestion also is important. Compared with fermentation in the rumen, digestion of starch in the small intestine and absorption of glucose obviates methane and heat losses associated with ruminal fermentation. Processing to increase digestibility in the small intestine also increases starch availability to rumen microbes. Increasing small intestinal starch digestion without severely depressing total tract digestion should improve conversion of feed to carcass gain and, consequently, reduce the quantity of feed needed by growing animals.

Particle Size Research-Dry Corn

A feedlot study was conducted to determine how corn particle size of dry corn grain affects rate and efficiency of gain, and starch digestibility. A relatively high roughage level (14% cottonseed hulls) was used to avoid intake depressions associated with unpalatability of finely processed corn. By removing the effect of feed intake on performance, we could concentrate on the effects of particle size. For 145 days, 33 yearling steers initially averaging 353 kg were fed grain rolled to three different particle sizes, fine, medium, and coarse.

Steers fed finely rolled corn had higher total tract starch and organic matter digestion. However, steers fed the medium particle size tended to have faster and more efficient gains and increased marbling scores. Although an increase in grain digestibility would be expected to improve feed efficiency, that was not true in this trial. Two explanations can be offered for this dilemma. First, steers fed fine diets may have suffered from subclinical acidosis which could result in higher maintenance energy costs. Second, the medium particle size may have increased flow of starch to small intestine and thereby enhanced energetic efficiency. However, it is seems unlikely that metabolic problems would be prevalent considering that tylosin was being fed and the diet contained a relatively high amount of roughage. Hence, the more logical explanation is that the quantity of starch digested in the small intestine was greatest with the medium particle size because the fine particles were more extensively fermented in the rumen and the coarse particles were less digestible in the small intestine.

Optimal particle size may be a moving target, changing as animals age. The largest particle size may be advantageous early in the feeding period while a smaller particle size improves feed efficiency later. This is because larger particles tend to increase feed intake early in the feeding period whereas late in the feeding period, when animals are older, they do not chew their feed as thoroughly and thereby digest coarse particles less extensively. However, results may only apply under certain conditions similar to ours, i.e., higher roughage diets fed ad libitum to yearling feedlot cattle.

Whole Corn/Limit Feeding Research

A feeding trial and a metabolism trials were conducted to examine the effects on rolled (fine or coarse) or whole corn and of limit feeding on feedlot performance and on ruminal fermentation.

In the feeding trial, 144 fall-born calves initally averaging 245 kg were fed high concentrate diets starting in July, September or November, 1994. Half the steers were given access to feed ad libitum or feed supply; for the other steers, intake was limited to 83% of the amount consumed by steers fed ad libitum for the first half of the finishing trial. Grain forms included finely (1,550 μm) and coarsely (3,100 μm) rolled corn or whole (5,700μm) corn. Steers were fed their diets for a minimum of 170 days. Ad libitum and limit fed cattle responded similarly to corn processing; however, ad libitum fed steers tended to showed more response to particle size. Steers fed coarsely rolled diets ad libitum tended to eat more feed and gain faster than those fed the whole or fine rolled diets. However, whole corn steers were more efficient than steers fed either finely or coarsely rolled corn. Fecal starch concentration increased as corn particle size during the first half of the feeding period but coarsely rolled corn tended to produce the highest fecal starch during the second half of the trial. Although the steers fed the fine rolled corn consistently had lower fecal starch concentrations, indicating that starch was more extensively digested, steers fed whole corn had superior feed efficiency. This might be attributed to differences in acidosis or site of digestion.

In the metabolism study, effects of whole or rolled (fine or coarse) corn on fermentation and total tract digestibility were examined with ruminally cannulated steers. Steers fed whole corn maintained a ruminal pH above 6.10 throughout the day compared with those fed finely and coarsely rolled corn for which pH dropped to 5.42 and 5.67, respectively. Proportions of propionate increased and acetate decreased as particle size decreased. Total VFA concentration at 17 hours post feeding also increased with smaller particles. These data indicate that rate and perhaps extent of ruminal fermentation was increased as particle size decreased.

Reasons for the efficiency advantage with whole corn are not fully clear but more stable ruminal fermentation and increased flow of digestible starch to the small intestine may be involved. However, the cost associated with processing may not be justified in terms of improved feedlot performance. Compared with more extensive processing methods like steam flaking, whole corn generally still has a poorer feed efficiency. However, feeding whole corn early in the feeding period and reserving processed grains for late in the feeding period should be considered.

Particle Size Research - High Moisture Corn

Feeding facilities at Panhandle State University were used to examine the effects of high moisture corn particle size and processing method on feedlot performance, carcass characteristics and ruminal fermentation of steers. High moisture corn (70% DM) was either rolled to three extents or ground before being ensiled. As ensiled and fed to 192 yearling steers (initally 334 kg) for 97 days was either finely rolled (1,280 μm), medium rolled (1,620 μm), coarsely rolled (2,120 μm) or ground (1,830 μm). Statistical analysis was used to determine the performance responses both to mean particle size and to standard deviation in particle size. Ground corn has a much wider particle size distribution than rolled corn which was quite uniform. During the first 39 days on feed, cattle fed the medium rolled (SD = 2.15) and coarsely rolled (SD = 2.25) corn tended to gain faster than steers fed finely rolled (SD = 2.04) or ground (SD =2.36). During the last 60 days, ADG increased as particle distribution increased. When averaged over the entire feeding period, gained tended to increase as particle distribution widened. In contrast, cattle fed ground corn (higher distribution) were more efficient during the final 60 d. Similar to the studies discussed previously, fecal starch content was higher and digestibility lower for steers fed ground high moisture corn, so again, enhanced digestibility of starch in the total digestive tract did not maximize feed efficiency.

Four ruminally cannulated steers were each pen fed with these feedlot cattle to examine ruminal effects. Ground corn produced higher propionate and lower acetate concentrations than other processing methods at 4 hours post-feeding. Lactate levels were elevated at 17 hours post-feeding by finely rolled corn reflecting very rapid ruminal fermentation.

Previous research from feeding trials Oklahoma State has shown an advantage of ground over rolled high moisture corn. The increased particle size distribution may both slow fermentation, reducing the likelihood of acidosis, and increase the flow of starch to the small intestine which may increase energetic efficiency. The proper mix of particles size may be as or more important than the mean particle size. Advantages from mixing grain types or processing methods for feedlot cattle also might be due to complementary ruminal fermentation patterns and a wider particle size distribution.

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VITA

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