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# Evaluation of Grain Type and Processing Method on Steer Performance, Carcass Characteristics, and Nutrient Digestion

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# EVALUATION OF GRAIN TYPE AND PROCESSING METHOD ON STEER PERFORMANCE, CARCASS CHARACTERISTICS, AND NUTRIENT DIGESTION

by

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A feedlot finishing study evaluated the effect of replacing corn with dry-rolled wheat in diets containing wet distillers grains plus solubles (WDGS; Exp 1). Two studies were conducted to evaluate the effect of corn type [dry corn (DC), high-moisture corn (HMC**)**, or a blend of dry and high-moisture corn (BLEND)] processed with either Automatic Roller Mill (ROLL) or hammer mill (HAMMER) on steer performance, carcass traits, and nutrient digestibility (Exp. 2 and 3). In Exp. 1, steers were fed diets containing 100% dry-rolled corn (DRC) or a 50:50 blend of dry-rolled corn and wheat (WHEAT) in diets containing 12 (12WDGS) or 30% (30WDGS) WDGS (DM-basis). Substituting corn with wheat in finishing diets did not influence performance or carcass traits in steers when fed for 158-d regardless of WDGS inclusion; however, feeding increased amounts of WDGS did increase final BW, HCW, and improved ADG by 4.1% and G:F by 4.4%. Wheat can replace up to 50% of corn in a finishing diet regardless of WDGS inclusion. In Exp. 2, a finishing trial evaluated feeding DC, BLEND, or HMC processed with ROLL or HAMMER to steers fed for 134 d. Steers fed ROLL HMC were 4.7% more efficient with 55% lower fecal starch compared to HAMMER HMC, with no other interactions between grain type and mill type. Experiment 3 evaluated DC or HMC processed with either ROLL or HAMMER on nutrient digestion. There was a tendency

for an interaction between corn type × milling method for DM and OM digestibility; however, there were no other interactions observed. Feeding HMC increased DM, OM, and starch digestibility compared to DC. Processing HMC with a roller mill improved feed efficiency compared to processing with a hammer mill, but milling method had little effect on performance or nutrient digestibility when fed as DC or BLEND.

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## Introduction

Feeding and processing grains to be fed to cattle is not a novel idea and can be traced back to the mid- to late-1800s although commercial cattle feeding was not prevalent until the 1940s. As commercial cattle feeding emerged, the need to capture more energy from feed to meet increased performance demands was required and was accomplished through grain processing (Matsushima, 2006). Furthermore, feed costs are the largest expense in feeding cattle, thus increased efficiency is necessary.

Dry-rolled wheat is the second most used cereal grain in finishing diets behind corn (Samuelson et al., 2016). Historically, feeding wheat has been documented as an acidosis concern due to its rapid rumen fermentation when used as the primary ingredient in beef cattle diets. However, in certain geographical areas and seasons, wheat may be an economical alternative to feeding corn (Lardy and Dhuyvetter, 2016). While feeding wheat has been done for many years, much of the prior research was done prior to the widespread use of distillers grains.

Roller mills and hammer mills are the most common machines for processing dry and high-moisture corns. Roller mills generally produce a more uniform particle size and are more energy efficient, but are more expensive to purchase and maintain compared to a hammer mill (Koch, 2002). Hammer mills are less costly to purchase and maintain; however, particle size is more difficult to control and are less energy efficient (Koch, 2002). None the less, processing of grains is vital to maximizing microbial efficiency in the rumen often times leading to improved animal performance.

# CHAPTER I. Review of the Literature

*Starch Utilization in Ruminants*

Starch is the main carbohydrate in cereal grains (Serna-Saldivar, 2010). Starch granules are largely composed of amylose and amylopectin. Amylose is a linear polymer composed of glucose with α-(1,4) glycosidic linkages and amylopectin is a branched polymer with both α-(1,4) and α-(1,6) linkages (Svihus et al., 2005). In cereal grains, the starch component can vary by grain with 57 to 58% in barley and oats, 72% in corn and sorghum, and 77% of DM in wheat (Huntington, 1997). The starch is deposited in granules within the protein matrix in the endosperm and generally consists of 1/3 amylose and 2/3 amylopectin, although this varies depending on grain type, maturity, and growing conditions (NASEM, 2016; Svihus et al., 2005). The protein matrix within the endosperm affects the starch availability and rate of digestion, which alters the rate of fermentation of different grains (NASEM, 2016).

Starch is the primary component and energy source in feedlot finishing diets. Starch, fed as cereal grains in finishing diets, is favored due to energy density and high digestibility and its relative price compared to forages (Huntington, 1997; Owens and Soderlund, 2006). Increased use of starch can make a well-managed system more productive and efficient. Altering the grain source, processing method, animal type, and management conditions can all affect the feeding value and starch utilization in the animal (Zinn et al., 2007). In a feedlot consultant survey conducted in 2015, nearly 80% of responding consultants (n=24) were using 60% or greater grain in the diet and of that, 100% of responding consultants were using corn as their primary grain source in finishing diets, followed by 50% using wheat as a secondary grain source (Samuelson et al., 2016).  Starch, from use of cereal grains, is an important and widely utilized energy source that increases efficiency in feedlot systems.

*Site and extent of starch digestion*

Cereal grains are composed of a thick, layered pericarp that encapsules the germ and endosperm and is resistant to microbial digestion (McAllister and Cheng, 1996). As previously mentioned, the endosperm consists of starch granules within a protein matrix on the surface of starch granules, called prolamins, unique to the individual grain type (NASEM, 2016). The combination of the thick pericarp and individual prolamins of each grain type are what drives the fractional rate of digestion in the rumen (McAllister et al.,1993). Unprocessed corn and sorghum are generally more-slowly and less extensively fermented in the rumen, whereas wheat and barley are rapidly fermented and nearly completely digested in the rumen (McAllister et al., 1993). Furthermore, differences in starch digestibility between cereal grains can be attributed to the degree of crystallinity and the ratio of amylose:amylopectin, with increased amylose possibly hindering digestion in unprocessed grains (McAllister et al., 1993; NASEM, 2016).

The bulk of ruminal fermentation is performed by ruminal bacteria, although protozoa and fungi also participate in rumen functions (Huntington, 1997). Approximately three-fourths of fiber, starch, and protein digestion is done by loosely or tightly attached bacteria to feed particles (McAllister et al., 1994). Some of these amylolytic bacteria adhere to an colonize on grain particles in the rumen and produce endo- and exo-enzymes that hydrolyze the bonds in amylose and amylopectin to produce monosaccharides (Kotarski et al., 1992). However, all starch-utilizing bacteria do not have the capabilities to produce every enzyme required for starch digestion, so complementary bacteria are required to efficiently digest cereal grains (McAllister and Cheng, 1996). Cross-feeding among *Streptoccocus bovis, Butyrivibrio fibrisolvens, Bacteriodes ruminicola,* and *Selenomonas ruminatium* and co-colonization with *Ruminobacter amylophilus* and *Prevotella ruminicola* has been shown to be the most effective at maximizing bacterial growth rates and complete digestion of starch (Cotta, 1992; McAllister and Cheng, 1996). However, it is important to note that whole kernel grain with an intact pericarp, is nearly resistant to ruminal digestion because the whole kernels are resistant to bacterial attachment, although this can be overcome through mechanical grain processing or chewing that breaks the pericarp (Huntington, 1997).

Although bacteria are responsible for much of the starch digestion in the rumen, protozoa, and fungi to an extent, are an important part of starch digestion. Ruminal protozoa engulf starch granules with or without bacteria attached (Huntington, 1997). The most significant impact of protozoa is thought to be the ability to regulate the rate of starch digestion through engulfed starch granules (McAllister and Cheng, 1996). Engulfed starch granules may take up to 36 h to be completely metabolized by the protozoa and protozoa may decrease the total population of amylolytic bacteria through predation. The combination of factors is thought to reduce rate of fermentation and help regulate ruminal pH (McAllister and Cheng, 1996; Mendoza et al., 1993; Ortega Cerrilla and Mendoza Martinez, 2003). The role of ruminal fungi in high-concentrate diets is lesser known. However, the relative number of protozoa typically increases with the addition of concentrate in the diets from $3.61 \times 10^5$ in forage-based diets to $8.03 \times 10^5$ in 75% concentrate diets (Franzolin and Dehority, 1996). There is some evidence of a fungal species producing an α-amylase enzyme (Mountfort and Asher, 1988) and it is thought that lesions caused from fungi may help with bacterial attachment (Huntington, 1997). However, there is little difference in fungi numbers in cattle fed high-concentrate diets compared to high-forage diets (McAllister and Cheng, 1996). Therefore, the true benefit of fungi in ruminal starch digestion is not well-known.

Increased digestible starch in the rumen, in general, is associated with increased production of organic acids (volatile fatty acids), increased production of microbial protein, decreased fiber digestion and decreased acetate:propionate ratio (Huntington et al., 2006). However, associations with ruminally fermented starch can vary greatly from animal to animal and is somewhat hard to predict due to the nature of group-fed animals (Huntington et al., 2006).

Ruminal starch digestion can vary greatly depending on grain type, processing method, and protein matrix of the grain; however, rumen starch digestion ranges from 64 to 87% for corn depending on processing method and up to 95% for rapidly fermenting grains such as barley (Owens and Soderlund, 2006; Waldo, 1973). Starch not digested in the rumen by microbes and protozoa containing starch granules enter the small intestine where it undergoes further digestion. The quantity of starch digested in the small intestine is directly related to starch flow and digestibility (Owens and Soderlund, 2006). Starch digestion in the small intestine occurs in three phases: action of α-amylase and bicarbonate from pancreatic secretion in the duodenum, digestion and absorption at the brush border membrane through brush boarder carbohydrases, and transport of glucose out of the intestinal lumen and into the portal vein to be taken to the liver for further metabolism (Huntington et al., 2006, Owens et al., 1986). Although digestion of starch in the small intestine is energetically favorable compared to the rumen due to fermentation losses, the capacity of the small intestine in ruminants to digest starch is limited (Ortega Cerrilla and Mendoza Martinez, 2003; Owens et al., 1986). The lack of intestinal starch digestion is a product of limited quantities of α-amylase, maltase and isomaltase and a limited ability to absorb glucose without adaptation of the host carbohydrases (Huntington et al., 2006; Ortega Cerrilla and Mendoza Martinez, 2003; Owens et al., 1986). Using pooled data, it is estimated that small intestine digestibility of starch is on average 62% of starch entering the small intestine; however, this depends on grain type and extent of processing with increased processing and moisture likely contributing to a greater percentage of starch entering the small intestine being digested (Harmon et al., 2004; Owens and Sonderlund, 2006). Using pooled data from Harmon et al. (2004), regressing starch digestibility and starch intake showed a negative slope, indicating that increased starch intake decreases digestibility, which is supported by the limitation of intestinal starch-degrading enzymes.

Total tract starch digestion in feedlot cattle is 87 to 99% of intake depending on grain type, protein matrix, and extent of processing (Owens and Sonderlund, 2006). Although the rumen is energetically costly to the host because of losses from fermentation, its capacity to degrade starch is an important advantage to the ruminant animal. Starch digested in the small intestine is a more direct source of glucose to the host; however, the animal's capacity to digest starch is limited and decreases with increased intakes. Understanding the mechanisms and alterations of starch digestion in ruminants is important to understand and appreciate the effects of grain type and processing methods on digestion and animal performance.

*Feeding small cereal grains in finishing diets*

Cereal grains have been the most important supplier of dietary energy to humans for more than 24 centuries (Serna-Saldivar, 2010). Cereal grains have been considered the backbone of agriculture with nearly 70% of global farmland planted to cereal grains (Serna-Saldivar, 2010) and have continued to be an important component for human and livestock diets. Common cereal grains include corn (maize), wheat, millet, rice, barley, oats, rye, triticale, and sorghum. Of those cereal grains, wheat, barley, oats, and rye are considered small cereal grains (Ishida et al., 2019).

The type of cereal grain utilized in beef cattle diets is largely dependent on geographical location. In the United States, the primary cereal grain utilized is corn, secondary is wheat, and followed by sorghum and barley (Samuelson et al., 2016; Vasconcelos and Galyean, 2007).  While corn is the primary grain source used, there are certain times where wheat, barley and other small grains may be priced competitively with corn due to damage from disease, drought or sprouting (Reed et al., 2005). Under these circumstances, wheat, barley, or other small grains may be a viable substitute for corn in feedlot cattle diets.

*Alterations in digestion and metabolism*

For the purpose of this review, wheat and barley will be the primary focus. Wheat and barley are similar in their chemical composition. Wheat has a digestible energy (DE) of 3.83 Mcal/kg, contains 62% starch (of dry matter), has 14% crude protein, of which is approximately two-thirds rumen degradable protein (RDP) and one-third rumen undegradable protein (RUP). Barley contains 3.7 Mcal/kg of DE, 57% DM starch, 13% crude protein, which is approximately 50% RDP and 50% RUP (NASEM, 2016).

Nearly 90% of all starch from wheat is digested in the rumen (Huntington, 1997; Owens et al., 1998). Wheat is the most rapidly fermented cereal grain, with approximately 10 to 11%/h disappearing *in vitro* compared to dry-rolled corn and sorghum at approximately 6.5%/h in vitro (Stock et al., 1990). Further mechanical processing of wheat (i.e. half or quartered kernels compared to whole kernels) increases the rate of starch disappearance in the rumen (McAllister et al., 1990). When evaluated *in situ*, whole kernels of barley, maize and wheat were nearly indigestible after 48-h incubation (11, 14, and 23% dry-matter digestibility, respectively). When kernels were halved, *in situ* dry-matter digestibility (DMD) of wheat and barley increased after just a 12-h incubation to 31 and 25%, respectively. Increasing the surface area by quartering the kernels further increased the *in situ* DMD to 60 and 51% for wheat and barley, respectively, after a 12-h incubation, although these numbers were not significantly different from halved kernels (McAllister et al., 1990). Scanning electron microscopy determined that the bacteria colonized on the kernels differed between wheat and barley and corn. The differences in bacteria present combined with differences in the physical and chemical properties, such as the endosperm and protein matrix, is responsible for the differences in rumen digestibility (McAllister et al., 1990).

Because of its rapid rumen fermentation, wheat-based finishing diets have been notorious for being an acidosis concern. Simply, acidosis is the decrease in basic compounds in the body fluids and increase in acidic content (Owens et al., 1998). Cattle experience acidosis following consumption of readily fermentable carbohydrates in quantities large enough to reduce ruminal pH. This can occur from improper adaptation from a forage-based diet to a high-concentrate diet, engorgement of a rapidly fermentable carbohydrate or when animals are switching from bulk fill to chemostatic energy regulation of intake (Owens et al., 1998). Commonly, subacute acidosis is manifested through decreased or erratic feed intakes and consequently decreased gain and/or feed efficiency (Cooper et al., 1999; Owens et al., 1998). Due to its reputation of causing acidosis in feedlot diets, it is not recommended to feed more than 40% of the diet DM as wheat (Lardy and Dhuyvetter, 2016).

The concept of erratic intake patterns caused by subacute acidosis when steers are fed rapidly fermented wheat compared to corn was demonstrated by Fulton et al. (1979). Steers were fed increasing amounts of concentrate (35, 55, 75, and 90% DM) for 20 days (5 days/concentrate level) and dry matter intake and rumen fermentation parameters were measured. Both corn and wheat fed steers declined in intake by day 5 of the 35% concentrate step; however, wheat fed steers continued to decrease intake after the change to 55% concentrate diet and did not increase until four days at 55% concentrate while corn fed cattle remained steady. Each increase in concentrate on day 1 for the wheat-fed steers led to a decrease in intake for respective diet. Furthermore, wheat-fed steers had greater variation in ruminal pH and greater frequency of pH values below 5.2 compared to corn-fed steers. While ruminal pH is also a function of intake and diet consumed, and may not be the sole indicator of acidosis, it is of note that smaller intakes of wheat-fed cattle yielded more dramatic drops in rumen pH compared to corn-fed diets, suggesting acidosis challenges.

Moya et al. (2015) compared feeding 89% barley grain or wheat and degree of processing on cattle performance and bunk behavior. The author reported that regardless of processing extent, wheat-fed cattle had a lower DMI compared to barley fed cattle.

Additionally, cattle fed wheat spent less time at the bunk per visit, ate less per visit, and spent less time daily eating compared to barley fed cattle. This alteration in feeding behavior of wheat-fed cattle may be in response to the greater energy content of wheat vs barley or may be a mechanism of feedlot cattle to avoid digestive upset. There was no effect on performance or carcass characteristics for cattle fed wheat compare to barley, but there was a tendency for cattle fed wheat to have a greater percent of total abscess classified as severe (A+) compared to barley, which may be an indicator of acidosis challenge.

Zinn (1992) compared feeding steam-flaked corn and steam-flaked wheat in finishing diets containing 12% roughage. Interestingly, there were no differences in growth performance between steam-flaked corn or steam-flaked wheat, with the exception of an increase in dietary net energy for steam-flaked corn. Furthermore, there were no differences between steam-flaked corn or wheat for carcass traits; however, cattle fed steam-flaked wheat had a greater percentage of retail yield compared to the carcass of cattle fed steam-flaked corn. There was no difference in abscessed livers.

To overcome the risk of acidosis when feeding rapidly fermentable grains such as wheat and barley, it is common to combine them with a slower fermenting grain such as corn or sorghum (He et al., 2015; Kreikemeier et al., 1987; Lardy and Dhuyvetter, 2016). Feeding rapidly fermented grains with slower fermenting grains results in positive associative effect, decreases the risk of acidosis, and improves starch utilization by altering site and extent of digestion (Kreikemeier et al., 1987). When lambs were fed a 100% rolled wheat, 100% whole corn, or a combination between the two, the lambs fed a combination of wheat and corn were on average 3.8% more efficient compared to only being fed one grain type (Kreikemeier et al., 1987). In agreement with the lamb trial, cattle fed a combination of wheat and corn were 4.4% more efficient compared to the average performance of cattle fed 100% of corn or wheat (Kreikemeier et al., 1987). Similar results occurred when wheat replaced high-moisture sorghum grain in finishing diets. As wheat increased relative to high-moisture sorghum grain, cattle consumed less, gained more, and were more efficient (Axe et al., 1987). Additionally, as wheat replaced high-moisture sorghum grain, total tract digestibility, starch digestibility, and total VFAs increased, while pH decreased slightly compared to feeding 100% high-moisture sorghum (Axe et al., 1987). Perhaps the greatest application of blending grains is during the step-up period when adapting cattle to larger concentrations of grains. Kreikemeier et al., (1987) demonstrated that cattle stepped up on a dry corn-based diet for 21 d, then transitioned to a diet containing 100% wheat had no adverse effects on performance compared to cattle fed a diet containing corn and wheat for the trial duration. This potentially suggests that control acidosis with slower fermenting grains such as corn during the step-up period is the most critical to animal performance. Similar results have been observed with other grain types and combinations (Bock et al., 1991; Huck et al., 1998; Stock et al., 1987).

It is generally accepted and recognized that wheat is an acidosis concern due to its rapid fermentation in the rumen but combining wheat with more slowly fermenting grains consistently results in positive associative effects and increases in ADG and feed efficiency compared to being fed a single grain type. This allows animals to benefit from the increased protein and ruminal fermentation wheat compared to corn or sorghum grain, possibly increase starch digestion to the small intestine where, although limited, is more energetically favorable compared to the rumen (Stock et al., 1987; Waldo, 1973), and mitigate acidosis occurrences.

*Addition of distillers' grains to small cereal grain diets*

Distillers' grains (corn- or wheat-based) have been a main constituent of beef cattle finishing diets for more than 20 years, especially in the Midwest corn belt. Differences in corn or wheat-based distillers' grains is reflective of the grain itself but is important to note that chemical composition of the feeds can vary widely between plants and batches. On average, corn distillers' grains are 30% crude protein (CP; DM-basis), 38.8% neutral detergent fiber (NDF), and are high in phosphorus and low in calcium (Liu, 2011). In contrast, wheat distillers' grains contain, on average, 38.1% CP, 32.6% NDF, and are lower in fat, higher in calcium and lower in phosphorus compared to corn distillers' grains (Olukosi and Adebiyi, 2013). While the literature is extensive on utilization of distillers' grains in corn-based growing and finishing diets, the literature is limited on its use in wheat-based diets. Because of the similarities in composition and ruminal fermentation of barley and wheat previously outlined, focus will be on the effect of distillers' grains in barley-based diets.

Distillers' grains are primarily a source of readily digestible neutral detergent fiber and high in protein but contains little to no starch due to fermentation and conversion to ethanol production (NASEM, 2016). Conceptually, when included in finishing diets, distillers' grains displace starch in the diet from cereal grains such as wheat or barley and may help maintain normal rumen fermentation without impacting the energy density of the diet (Eun et al., 2009).

Li et al., (2011) replaced barley grain and barley silage with wheat-based dry distillers' grains with solubles (DDGS) in finishing diets to evaluate if DDGS could adequately replace both energy and fiber. When DDGS was included at 25% of the diet dry matter, there was no effect on DMI or OM intake, whereas CP intake was greater and starch intake was lower when DDGS replaced barley grain and silage. More interestingly, ruminal pH parameters were unaffected with the inclusion of 25% DDGS compared to the control diet; however, when wheat DDGS was increased to 35% of diet DM, rumen pH decreased and duration of pH <5.5 and <5.2 were greater compared to the control.

A feedlot performance study also evaluated the effect of replacing barley grain and barley silage with 25, 30, or 35% wheat based DDGS (Yang et al., 2012). When wheat DDGS replaced barley and barley silage at 25% diet DM, DMI increased compared to the control (11.6 vs 10.9 kg/d), but as DDGS was increased to 30 and 35%, DMI linearly decreased (11.3 vs 10.7 kg/d). There were no differences in final BW, ADG, or feed conversion for any of the treatments. Furthermore, as DDGS was included in the diet, steers spent more time eating, ate slower, and visited the bunk more frequently than the control diet. However, the results of including DDGS in the diet at 30 or 35% should be interpreted with caution as barley silage was included at 5 or 0% of diet DM, respectively, and was the only source of roughage in the diet, potentially challenging the cattle from an acidosis perspective.

These data are consistent with Gibb et al., (2008), who observed a linear increase in DMI as barley grain was replaced with wheat DDGS from 0 to 60% of diet DM. Increasing DMI combined with no difference in ADG resulted in a linear decline in G:F for cattle fed increasing concentrations of DDGS. The decline in G:F from the increase in

DMI is likely a result from increasing NDF (Galyean and Defoor, 2002) and decrease in starch, which is consistent with high inclusions of DDGS. Furthermore, the author also credits the potential for pH moderation from displacing rapidly fermented barley grain for the increase in DMI with increasing inclusion of DDGS.

Eun et al. (2009) replaced barley grain with 10.5 or 17.5% corn DDGS in finishing diets and found steers with DDGS included in the diet at either level had similar final BW to the control, but DDGS inclusion significantly decreased DMI and had no effect on ADG, which led to a tendency for an 11.5% improvement in feed efficiency compared to a control diet containing no DDGS. Furthermore, there were no differences in digestibility or ruminal pH between the control diet and the diet containing 17.5% DDGS, but there was a tendency for a reduction in total VFA production when DDGS was included in the diet with no differences in the individual VFA profiles (Eun et al., 2009).

Wheat-based distillers' grains are commonly seen as replacements for barley grain, likely due to the geographical locations where both wheat and barley are common. However, there are inconsistencies in the data between corn distillers' grains and wheat distillers' grains when replacing barley in finishing diets. Amat et al. (2012) fed approximately 40% corn, wheat, or blended DDGS in a barley grain-based diet to finishing steers. Consistent with previous results, wheat DDGS increased DMI compared to the control diet (10.2 vs 9.8 kg/d; Gibb et al., 2008; Yang et al., 2012). Corn and blended DDGS DMI was intermediate; however, corn and blended DDGS diets had greater ADG, which led to a 7.5 or 9.2% improvement in G:F when corn or blended DDGS were included in a barley-based diet compared to wheat DDGS. The increase in performance when cattle are fed corn or a corn-wheat blended DDGS can be attributed to corn DDGS being a superior energy source to wheat DDGS when fed at 40% of the diet DM.

Wheat or corn distillers' grains can replace a portion of barley grain in a finishing diet without compromising performance. Wheat distillers' grains consistently increase DMI, with no effect on ADG, which in turn decreases G:F slightly compared to no distillers' grains. Corn based distillers' grains generally decrease DMI, increase ADG, and improve G:F compared to cattle fed no distillers' grains. The benefit of corn distillers' grains is likely due to a greater energy content of corn distillers compared to wheat. Additionally, the increase in DMI of wheat distillers' grains and the improved performance observed with corn distillers' grains suggest that displacing at least part of the starch in the finishing diet is favorable for feedlot performance, but corn-based distillers likely has little effect on ruminal pH and acidosis control. This is evident in data from Corrigan et al. (2009), who observed steers fed 40% corn based WDGS had lower maximum pH but less pH variance compared to steers fed 0% WDGS, with little effect on other pH parameters. Vander Pol et al. (2009) also observed little effect on pH when steers were fed 40% corn based WDGS compared to 0% WDGS in finishing diets.

*Economics of feeding small grains*

Wheat that is economical to feed in beef cattle ration is often discounted for a variety of reasons, generally caused by drought, insects, or wet conditions at harvest (Lardy and Dhuyvetter, 2016). Wheat under these conditions fail to make the quality standards for flour milling and may be sold at a discount as feed wheat (He et al., 2015). Sprouted wheat occurs when moisture is plentiful near harvest time and delays the harvesting of small grains. Feeding sprouted wheat has no effect on beef cattle performance when fed in a finishing diet, regardless of the number or proportion of sprouted kernels (Lardy, 1999; Rule et al., 1986). Economically, Stewart (2017) found that the price of damaged wheat must be at least $0.06 cheaper per bushel than corn to be an economical replacement; however, as the price of corn increases, sprouted wheat loses its advantage and must be priced $0.10 to $0.14 less per bushel than corn to be considered favorable. Low test weight grains are useful as cattle feed but has smaller and less uniform kernel sizes, which makes processing difficult and inconsistent (Lardy and Dhuyvetter, 2016). Perhaps of more concern is mold, vomitoxins, and ergot that can be present in detrimental levels in damaged wheat. While there are data that suggest cattle can handle increased levels of vomitoxins without adverse performance, caution should be exercised with molds and ergot, which can reduce feed intake and affect performance (Lardy and Dhuyvetter, 2016).

Wheat is generally priced higher than corn per bushel. However, during certain times of the year and in certain geographical locations, the price of wheat and corn may become competitive or wheat may fall below corn. These scenarios occur during wheat harvest, in times of an abundant crop of wheat and depleted corn crop, or when considering local basis on corn in regions where wheat is more widely grown, such as the Texas Panhandle and Kansas (Hutchins, 2019). However, while prices differ on a per bushel basis, prices should be evaluated based on dollars per dry ton due to differences in moisture content and bushel weights for the two grains.

Overall, wheat is a rapidly fermentable grain that provides an adequate source of energy and protein to ruminant diets. Although wheat is commonly regarded as an acidosis concern, combining wheat with a slower fermenting grain, such as dry-rolled corn, or replacing part of the grain with corn or wheat distillers grains may help maintain a favorable rumen pH and actually increase performance compared to feeding wheat grain alone. Wheat is generally priced higher than corn per bushel but can become an economical option in beef cattle diets when damage occurs from natural causes or during particular times of the year and in certain geographical locations.

*Corn type and processing methods in finishing diets*

Historically, feeding grain-based diets to cattle can be traced back to early 1800s in Ohio (Matsushima, 2006). The first corn sheller and hammer mill were invented in the 1840s, but commercial cattle feeding did not begin to emerge until the 1940s (Matsushima, 2006). Several grains were available to be utilized for livestock feeds, but varied greatly in size, shape, texture, and chemical composition; therefore, processing was utilized to improve animal efficiency by altering the physical and chemical composition of the grains (Matsushima, 2006). Processing grains is simply damaging the kernel and reducing particle size of a grain either with or without the addition of steam or water (Owens and Sonderlund, 2006).

Most feedlots generally choose the grain type and processing method based on grain cost plus the cost of processing (Owens et al., 1997). There have been a variety of processing methods extensively reviewed and utilized that vary in cost and effectiveness, all with the primary goal of increasing starch availability and animal performance. In the U.S., the primary processing methods in finishing diets are steam-flaking, dry-rolling or dry-grinding, and high-moisture ensiling (Samuelson et al., 2016). Proper processing of corn will increase digestibility by at least 5 to 10 percent compared to feeding whole corn in finishing diets (Lardy, 2018).

Dry-rolled or dry-ground corn is one of the most cost-effective methods for processing corn (Bauer et al., 2017). It is generally achieved by using a hammer mill or roller mill where grains are sheared, and seed coat disrupted, to reduce particle size (Koch, 2002). By decreasing particle size, more surface area is exposed, allowing for increased microbial digestion of starch and protein (Koch, 2002). While sufficient processing is needed to maximize digestion, over-processing may result in too small of particle size with a rapid rate of ruminal fermentation, leading to metabolic disorders, such as acidosis (Owens et al., 1997).

High-moisture grain is harvested shortly after physiological maturity, but with optimum moisture that allows for easy harvest and low field loss, but still sufficient for proper fermentation (Mader and Rust, 2006). An acceptable moisture range to maximize yield and fermentation is between 25 and 33% (Mader and Rust, 2006). Moisture content between 20 and 24% typically results in poorer animal performance compared to drier or wetter grains, for unknown reasons (Owens, 2005). After harvest, high-moisture grain can then be rolled or ground prior to packing and ensiling in a bunker, trench silo, bagging system or other air-tight structures (Mader and Rust, 2006).

Steam-flaking corn is most often utilized by large commercial facilities as the main method of processing corn. Steam-flaking is accomplished by steaming whole grain at atmospheric pressure for a specific amount of time (usually 20 to 40 minutes), then the grain is passed through corrugated steel rolls and “flaked” to a density of 24 to 32 lb/bushel (Armbruster, 2006). Steam-flaking corn causes sufficient disruption to the starch-protein matrix and gelatinization of the starch to result in increased starch digestibility in the rumen and total tract (Armbruster, 2006). Total tract starch digestibility for SFC is consistently between 98.9 to 99.8% of total starch, which is an improvement of 4 to 10% over a DRC control (Cooper et al., 2002; Huntington, 1997; Zinn et al., 1995).

Capacity of the feedlot, local and regional corn pricing and basis, availability of other ration ingredients, and energy costs all play an important role in determining corn processing method for feedlots (Peters, 2006). Traditionally, steam-flaked corn has been the gold standard of corn processing; however, the widespread availability and use of wet distillers grains may have an impact on processing method chosen by a feedlot. However, feeding upwards of 35 to 40% WDGS in DRC-based diets has been consistently shown to give similar ADG and G:F compared to SFC-based finishing diets, and ADG and G:F is hindered when increasing levels of WDGS are included in SFC-based diets (Buttery et al., 2013; Corrigan et al., 2009). The availability of both corn and corn by-products gives the Midwest a competitive advantage when it comes to other methods of corn processing such as DRC and HMC.

Macken et al. (2006) calculated the cost of grain processing for a 5,000 or 20,000-head feedyard feeding dry-rolled corn, high-moisture corn or steam-flaked corn at 85% of diet DM. Logically, the cost of processing per ton of corn for each processing method was greater for a 5,000 head feedyard compared to 20,000-head due to inevitable fixed costs spread across tons of corn processed. In a 5,000-head feedyard, processing costs were \$1.58/t (metric ton) for dry-rolled corn, \$4.71/t for ensiled high-moisture corn, and \$9.57/t for steam-flaked corn. These costs decreased in a 20,000-head feedyard to

$0.81, $3.07, and $6.23 per metric ton for dry-rolled corn, high-moisture corn, and steam-flaked corn, respectively. Based on these costs, cattle fed high-moisture corn or steam-flaked corn would have to be 2.4 or 6.1% more efficient than cattle fed dry-rolled corn in a 5,000 head feedlot. These required improvements would be decreased to 1.7 and 4.2% for high-moisture and steam-flaked corns, respectively, in a 20,000 head feedlot. These factors must be considered on an individual feedyard basis to choose the most appropriate processing method.

*Alterations in site and extent of digestion*

As previously outlined, starch digestion in cattle primarily occurs in the rumen. However, it has been well-documented that site and extent of digestion differs among corn processing methods, but regardless of method, proper processing of grains will improve the total tract digestion of starch (Hale, 1973). Primary factors that influence the site and extent of digestion is particle size and surface area available for microbial digestion and the protein or fiber matrix in which starch is embedded in (Owens and Sonderlund, 2006). In high-concentrate feedlot diets, ruminal and total tract starch digestion are greater with fermented feeds, such as high-moisture corn due to microbial acidification and softened particles (Owens and Sonderlund, 2006; Owens and Basalan, 2016). In a review by Owens and Zinn (2005) of 51 published and unpublished studies, high-moisture corn had the greatest ruminal starch disappearance, followed by steam-flaked corn, and dry-rolled corn having the least amount of starch disappearance in the rumen (91.8, 84.9, and 68.3%, respectively). Furthermore, Cooper et al. (2002) saw similar results and apparent ruminal starch digestibility was 91.7, 89.6, and 76.2% for high-moisture, steam-flaked and dry-rolled corns, respectively. These results are consistent with the results previously observed by Galyean et al. (1976), who found that ground high-moisture corn had the greatest ruminal starch digestion (89.3%) followed by steam-flaked (82.9%) and dry-rolled corn (77.8%). Increased and proper processing and gelatinization of starch granules increases rumen digestibility through improved efficiency of rumen microorganisms, thus improving utilization of grain through feed required per unit of gain (Hale, 1973; Owens and Sonderlund, 2006; Rahimi et al., 2020).

Starch that is not digested in the rumen enters the small intestine. Energetically, the small intestine is more favorable than the rumen or large intestine due to reduced methane and heat losses from fermentation (Hales, 1973; Huntington et al., 2006; Owens and Sonderlund, 2006). While digestion in the small intestine generally plays a small role in feedlot diets, the importance of post-ruminally digestion increases as the extent of ruminal digestion decreases (Owens and Sonderlund, 2006). As a percent of total starch intake, dry-rolled corn has a greater percentage of starch digestion in the small intestine compared to high-moisture or steam-flaked corn (Owens and Zinn, 2005; Owens and Sonderlund, 2006). The starch entering the small intestine from steam-flaked corn is more digestible (92.6% of starch entering) than that of high-moisture corn (67.8%) or dry-rolled corn (68.9%; Huntington, 1997; Owens and Zinn, 2005). The combination of increased ruminal fermentation of high-moisture corn and increased post-ruminal digestion of steam-flaked corn contributes to total tract starch digestibility that was not different for high-moisture or steam-flaked corns but greater than that of dry-rolled corn (99.2, 99.1, 92.2%, respectively; Huntington, 1997; Owens and Zinn, 2005).

Dry matter intake, ruminal passage rate, and diet composition can influence the site and extent of starch digestion. Increasing starch intake decreases starch digestion in the rumen, likely due to an increased rate of passage and less retention time in the rumen (Rowe et al., 1999). This relationship is less clear with steam-flaked corn, where increased dry matter intake increases the percentage of starch fermented in the rumen, possibly due to increased viscosity of the rumen fluid and therefore increased retention times (Rowe et al., 1999). Diets high in protein or high in dietary NDF decreases rumen starch digestion and shifts the site of starch digestion towards the small intestine (Owens, 2005). In contrast, high starch-low fiber diets, such as a common feedlot diet, increases rumen starch digestion (Owens, 2005).

*Effect on cattle performance*

Through changes in site and extent of starch digestion, processing grains can improve the nutritive value of grains, thus improving animal performance (Litherland, 2006). From a diet formulation standpoint, the benefit of processing methods is accounted for through increased energy captured from feed, expressed as either TDN or Mcal/kg of net energy. The increase in TDN values, energy availability, and ultimately improvement in feed efficiency yields increased daily gains, therefore potentially increasing economic returns (Peters, 2006).

A review completed by Owens et al. (1997) evaluated different corn processing methods in diets that contained at least 55% corn grain and no more than 15% roughage (DM-basis). Across 16,228 head of cattle, more extensive processing (i.e. from dry-rolled corn to steam-flaked corn), DMI was decreased and likely attributed to a slight reduction in ADG when more extensively processed grains were fed. The author suggests that the decrease in DMI and ADG may be due to an excessive rate of acid production and subclinical acidosis commonly observed in heavily processed grains. However, there was still an improvement in feed efficiency observed with more extensively processed grains, which supports increased energetic efficiency with increased processing. Body weight-adjusted metabolizable energy (Mcal/kg of DM) content of the processed grains increased from 3.21, 3.43, and 3.71 for dry-rolled corn, high-moisture and steam-flaked corns, respectively. Additionally, means for cattle fed high-moisture corn were compared, and as moisture content of the high-moisture corn increased, DMI decreased, ADG remained the same, contributing to an improvement in feed conversion and metabolizable energy content with higher moisture content.

Like wheat-based diets, associative effects between slower and rapidly fermenting processing methods can be used to mitigate subacute acidosis and improve performance in diets primarily corn-based. In the Midwest, it is common to combine rapidly fermenting high-moisture corn with slower fermenting dry grains, such as dry-rolled corn or sorghum (Stock and Erickson, 2006). Over nine trials conducted at the University of Nebraska, cattle fed either 100% dry-rolled corn or high-moisture corn had similar ADG and feed conversions. However, when cattle were fed a combination of 67-75% high-moisture corn and 33-25% dry-rolled corn, ADG was improved by 2.9% and feed conversion was increased by 4.3% compared to feeding high-moisture or dry corn alone. Furthermore, when dry-rolled corn or high-moisture corn were combined 33:63 with steam-flaked sorghum, a positive associative effect of 6.4% for ADG and 5% for G:F were observed compared to feeding dry-rolled or high-moisture corn alone (Huck et al., 1998). As expected, hot carcass weights tend to increase slightly with improved performance observed with combining processing methods, with no other significant effect on carcass traits (Huck et al., 1998).

Interestingly, similar associative effects can be observed when feeding whole corn with a processed grain, such as fine ground or rolled dry corn (Stock, 2006; Turgeon et al., 2010). When whole corn was added to replace the roughage content at 7.5 or 15% diet DM in diets containing high-moisture corn and steam-flaked sorghum, there was a slight decrease in DMI and ADG compared to no whole corn; however, a numerical increase in feed efficiency was observed (Turgeon et al., 2010). Furthermore, when whole corn replaced the roughage in finishing diets containing high-moisture corn and steam-flaked sorghum, final body weight, DMI and ADG decreased, while G:F increased slightly. Similar trends hold true when whole corn replaced the roughage in diets containing dry-rolled corn and steam-flaked sorghum (Turgeon et al., 2010), suggesting that whole corn shifts the site of starch digestion in the animal and helps mitigate acidosis concerns.

*Effect of particle size on performance*

Alterations in the particle size of processed corn may also influence the site and extent of starch digestion. Generally, finely-ground corn is more extensively digestible in the rumen compared to coarser ground grains and often times, increased ruminal digestibility increases total tract digestibility, but may not always improve animal performance (Owens et al, 1986; Secrist et al., 1995). Although decreasing particle size is an effective way to improve animal performance, over processing of corn, resulting in too fine of particle size, can cause rapid fermentation in the rumen leading to acidosis (Lundy et al., 2015).

Turgeon et al. (1983) fed 5 different diets to finishing steers with varying particle size: whole corn (5977 μm), cracked corn (2232 μm), fine ground corn (734 μm), a 50:50

blend of whole corn and cracked corn, or a 50:50 blend of whole corn and fine ground corn to evaluate the effect of particle size on performance. Steers fed the whole-cracked corn blended diet were heavier, gained more and were more efficient compared to whole corn with similar dry matter intakes. Compared to the cracked corn diet, the blended diet tended to improve feed efficiency but had no effect on final BW, ADG, or DMI. Whole corn blended with fine ground corn improved final BW, ADG and DMI compared to whole corn; however, there was no improvement in feed conversion. Fine ground corn had no effect on performance compared to whole corn blended with fine ground corn. Starch digestion increased as corn was more intensely processed, although that did not maximize performance in this trial.

Galyean et al. (1981) showed that regardless of corn type (steam-flaked, high-moisture or dry-rolled), dry matter disappearance in the rumen increased as the particle size decreased from 3000 µm to 750 µm (4.5% vs 18.4%). The percentage of starch disappearance was also greater for smaller particle size. The effect of particle size on percentage of disappearance was particularly noticeable in high-moisture and dry-rolled corns compared to steam-flaked corn. However, it is important to note that washout may be a problem in *in situ* work and digestibility values observed may be higher than actual values due to losses in the methods, therefore results should be interpreted with caution. Similarly, Schwandt et al. (2016) observed increasing *in situ* DM disappearance as corn was processed course (4882 µm), medium (3760 µm), or fine (2359 µm). The author reported decreasing particle size by 1,400 µm from medium to fine increased DM disappearance nearly 2-fold (31.4 vs 58.7%, respectively). Starch disappearance was also increased as particle size decreased, which agrees with Galyean et al. (1981). While *in* *situ* digestibility was clearly improved, there was no effect on feedlot finishing performance based on extent of dry-rolled processing with diets fed 20% wet distillers' grains, except for a reduction in DMI in the last 5 weeks as corn was more extensively processed. The author suggests that subacute acidosis commonly observed with smaller particle size may be the cause due to no differences in ADG or feed conversion.

Macken et al. (2006) evaluated the effect of dry-rolled (4730 µm), fine-ground (515 µm), rolled high-moisture (2901 µm), ground high-moisture (484 µm), or steam flaked (3117 µm) corn on steer performance and in vitro digestibility in diets containing 25% wet corn gluten feed (Sweet Bran). Dry matter intake decreased as cattle were fed high-moisture corn or steam-flaked corn compared to dry corns with no differences between processing methods. There were no differences observed in ADG, and combined with the decreased in DMI, G:F was improved by 5.6% for steers fed high-moisture corns and 9.3% for steam-flaked corn compared to dry corns regardless of particle size when Sweet Bran was included at 25% of the diet. Furthermore, fecal starch percent, which may be an indicator of diet digestibility, was decreased from 19.2% when cattle were fed dry-rolled corn to 4.1% in the steam-flaked corn diet, with rolled high-moisture corn and ground high-moisture corn having fecal starch percentages of 10.6 and 8.4%, respectively. Dry matter and starch disappearance in vitro were increased for rolled high-moisture corn and ground high-moisture corn compared to dry rolled corn or fine ground corn, which is consistent with Galyean et al. (1981). Scott et al. (2003) observed similar results as Macken et al. (2006) when dry-rolled, steam-flaked, fine ground or high-moisture corns were utilized, and wet corn gluten feed (Sweet Bran) was included at 32% of the diet. Feed efficiency was improved by 6.2, 4.8, and 3.7% over dry-rolled corn for steam-flaked, high-moisture, and fine ground corns, respectively. These data suggest that wet corn gluten feed may help mitigate acidosis concerns commonly observed with more extensively processed grains and decreased particle size.

Mader et al. (1991) performed three experiments to evaluate the effect of processing method and particle size of high-moisture corn on steer performance. Cattle were fed diets consisting of 79-83% corn and 10% corn silage as the roughage. High-moisture corn treatments included: whole high-moisture corn (7620 µm), ground high-moisture corn (2480 to 3840 µm; avg: 3303 µm), rolled high-moisture corn (3180 to 4750 µm; avg: 3965 µm), or a combination of whole high-moisture corn and ground or rolled high-moisture corn (4470 to 5240 µm; avg: 4855 µm). As seen in previous work, as degree of processing and particle size decreased (whole kernel to ground high-moisture corn), ADG and DMI decreased. However, ADG for cattle fed rolled high-moisture corn was similar to that of cattle fed whole high-moisture corn, but consumed significantly less, leading to an improvement in feed conversion for rolled high-moisture corn compared to all other treatments. As expected from previous research, ground high-moisture corn was perceived to be the most ruminally digestible, but had the poorest feedlot performance, suggesting acidosis may play a role.

Overall, decreasing corn particle size increases rumen starch digestion, but does not necessarily improve animal performance. High-moisture corn processed too fine may cause digestive disturbances. Dry corn must be processed more extensively to optimize performance, but again, too small of particle size may hinder performance and cause acidosis. Some research suggests that addition of corn by-products (i.e. wet corn gluten feed) may help mitigate acidosis risk from more extensively processed grains and optimize performance.

*Interactions with corn by-products*

Over the last 20 years, the grain milling industry has made corn milling by-products a viable and economical option to be used in beef cattle rations as both an energy and protein source. In 2015, nearly 97% of surveyed consulting feedlot nutritionists used grain by-products in finishing diets, with 71% using wet distillers' grains (WDGS) as the primary by-product (Samuelson et al., 2016). Common inclusions for WDGS ranges from 10 to 20% of diet DM, with an average of 16.5% in finishing diets (Samuelson et al., 2016). The addition of corn by-products, specifically WDGS, may displace starch in the ration by replacing corn and alter rumen fermentation, which in turn may help mitigate negative effects previously observed with extensively processed grains.

Vander Pol et al. (2008) fed 30% WDGS to cattle in diets that contained 61.4% of diet DM as whole corn, fine ground, dry-rolled, dry-rolled and high-moisture blend, high-moisture, or steam-flaked corn. The author determined degree of processing by fecal starch concentrations and concluded that degree of processing increased as follows: Whole corn, fine ground corn, dry-rolled corn, blend of dry rolled and high moisture corn, high-moisture corn, and steam-flaked corn. Cattle fed fine-ground corn were the lightest, gained the least, and consumed the least compared to any treatments. Final BW was the greatest for cattle fed dry-rolled and blend of dry-rolled and high-moisture corn, although the blended diet was not different than high-moisture corn alone or whole corn. Cattle fed steam-flaked corn with 30% WDG were lighter than dry-corn, high-moisture corn, or blended diets, but were greater than that of fine-ground corn. As degree of processing increased, with the exception of fine-ground corn, DMI decreased. Average daily gain was greatest for dry-rolled corn-fed cattle and blended and high-moisture corn-based diets were intermediate. Whole corn-fed cattle gained more than cattle fed steam-flaked corn. Feed efficiency was improved by 10.1%, 7.6%, 6.4% and 5.1% over whole corn for high-moisture, blended, dry-rolled, and steam-flaked corn-based diets, respectively. Fine ground corn was 1.3% less efficient compared to whole corn-based diets, which is likely due to its acidosis potential. Not surprisingly, HCW followed similar trends as final BW, with cattle fed dry-rolled corn and 30% WDGS having the heaviest HCW. These data suggest that performance is increased for dry-rolled and high-moisture corn-based diets, but adverse effects on performance are observed when steam-flaked or fine-ground corns are utilized and WDGS is included at 30% of the diet.

Corrigan et al. (2009) evaluated the effect of 0, 15, 27.5, or 40% WDGS inclusion (DM basis) in dry-rolled, high-moisture or steam-flaked corn diets on steer performance, feeding behaviors, and rumen parameters. For dry-rolled corn-based diets, increasing inclusions of WDGS linearly increased final BW, ADG, and feed conversion. Not surprisingly, hot carcass weight and dressing percentage were also linearly increased with increasing inclusions of WDGS in dry-rolled corn diets. Cattle fed high-moisture corn diets responded quadratically to increasing levels of WDGS, with final BW, ADG, and feed conversion optimized at 15 to 27.5% WDGS inclusions. Cattle fed steam-flaked corn also responded quadratically to increasing WDGS, although final BW, ADG, and feed conversion were consistently maximized at 15% WDGS. There was no interaction between corn type and WDGS inclusion for DMI, although DMI responded quadratically across all corn types in response to WDGS inclusion. The author also evaluated the effect of corn type with either 0 or 40% WDGS inclusion on digestion, intake patterns and rumen pH. No corn type × WDGS interactions were observed for intake or apparent total tract digestibility, although 40% WDGS increased DM intake, OM intake, NDF intake, and decreased starch intake compared to 0% WDGS. There was no corn type × WDGS inclusion interactions for intake patterns, except for time spent eating per day where cattle fed 0% WDGS and dry-rolled corn spent the least amount of time eating per day compared to any other diet. Finally, there were no interactions between corn type and WDGS inclusion for rumen pH parameters. However, cattle fed steam-flaked corn had a lower minimal pH, higher maximum pH, greater pH variance, and spent more time under pH < 5.3 compared to cattle fed dry-rolled or high-moisture corn diets.

More recently, Lundy et al. (2015) fed cracked corn (2350 µm) or fine ground corn (500 µm) with 35.2% WDGS (DM basis) to steers to evaluate the effect of processing extent and WDGS inclusion. Consistent with Vander Pol et al. (2008), final BW, ADG, and DMI were decreased when cattle were fed fine ground corn with WDGS compared to cracked corn. Feed conversion was not different between the treatments. Cattle fed fine ground corn had 12 kg lighter carcasses compared to cracked corn. Although there was no indication of acidosis based on similar liver abscess scores, seemingly increasing starch availability from extensive processing was not enough to overcome the decrease in DMI and ADG, therefore not eliciting a performance response.

Feeding WDGS in corn-based diets potentially changes the optimum processing method to maximize performance. Historically, steam-flaked corn has had an energy and performance advantage compared to dry-rolled or high-moisture corn in diets without corn by-products. However, feeding increased levels of WDGS, such as 20 to 30%, is advantageous in high-moisture, dry-rolled or blended diets, and equalizes or improves performance compared to steam-flaked corn diets. This is especially beneficial to operations where steam-flake systems are not a feasible option and allows performance to be increased with readily available feed sources.

## Conclusions

Cereal grains are an important dietary ingredient in ruminant diets, especially feedlot finishing diets. Understanding rumen fermentation of different cereal grains and alterations in site and extent of starch digestion based on grain type is vital to understanding expected animal performance and diet composition. Feeding wheat in finishing diets is a viable option, but its rapidly fermentable starch must be considered to avoid occurrence of acidosis. Processing of corn grain is used to alter the site and extent of starch digestion through particle size reduction and influence performance. Although historically more extensive processing has increased performance through increased surface area for microbial attachment and gelatinization of starch granules; the widespread use of corn by-products, such as WDGS, has shown using dry-rolled or high-moisture corns in combination with WDGS may maximize performance. Therefore, the objectives of these experiments were to: evaluate the effect of replacing corn with wheat in finishing diets containing 12 or 30% WDGS on steer performance and carcass traits (Exp. 1) and evaluate the effect of corn type and milling method on steer performance, carcass characteristics, and digestion in cattle finishing diets containing wet distillers' grains (Exp. 2 and 3).

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# CHAPTER II. Evaluation of wheat blended with corn in finishing diets containing wet distillers grains plus solubles

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## Abstract

A 158-d feedlot finishing experiment was conducted to evaluate the effect of grain type and wet distillers' grains inclusion on steer performance and carcass characteristics. Yearling steers (n = 320; initial BW = 325 kg; SD = 23 kg) were utilized in a 2 × 2 factorial arrangement, with the first factor as grain type with either 100% dry-rolled corn (**DRC**) or a 50:50 blend of dry-rolled corn and dry-rolled wheat (**WHEAT**), and the second factor as wet distillers' grains plus solubles (WDGS) inclusion at 12 (**12WDGS**) or 30% (**30WDGS**) of diet DM. There were no interactions ($P \geq 0.21$) between grain type and WDGS inclusion for any performance or carcass traits. There were no differences ($P \geq 0.29$) in DMI, ADG, or G:F between DRC or WHEAT. Cattle fed DRC and WHEAT had similar HCW ($P = 0.84$), but LM area was greater ($P = 0.02$) for steers fed WHEAT. There were no differences ($P \geq 0.15$) in 12$^{th}$ rib fat or USDA marbling score between grain types, but increased LM area in steers fed WHEAT led to an improved ($P$ = 0.04) calculated yield grade. Increasing WDGS in the diet increased ($P$ = 0.03) carcass-adjusted final BW and improved ($P \leq 0.05$) ADG and G:F by 4.1% and 4.4%, respectively. Hot carcass weight was improved ($P$ = 0.03) by 6 kg and 12$^{th}$ rib fat was greater ($P$ = 0.02) for HIGH compared to LOW. There were no differences ($P \geq$ 0.13) in LM area or USDA marbling score based on WDGS inclusion, but calculated yield grade tended ($P$ = 0.09) to be lower for 12WDGS. These data suggest that increasing WDGS in the diet improves performance regardless of grain type, and dry-rolled wheat can replace up to 50% of the grain portion of the diet without affecting performance in finishing diets.

**Key words:** Corn, distillers' grains, starch, wheat

## Introduction

Feeding dry-rolled wheat as a grain source in finishing diets is not a new concept and is the second most used cereal grain behind corn (Samuelson et al., 2016). However, because of its rapid ruminal fermentation, wheat is commonly regarded as an acidosis concern when included as a primary ingredient in beef cattle diets. To overcome the risk of acidosis, it is common to combine rapidly fermented grains, such as wheat, with slower fermenting grains, such as dry-rolled corn. The combination of grains generally results in a positive associative effect, by managing the risk of acidosis while improving starch utilization (Kreikemeier et al., 1987).

In certain geographical locations and time of year, wheat may become an economical alternative to feeding corn, especially when discounted for reasons caused by drought, insect damage, or wet conditions at harvest (Lardy and Dhuyvetter, 2016).

Furthermore, wheat may be priced competitive with corn at the time of wheat harvest, in times of abundant wheat crop and depleted corn crop, or when considering local basis on corn in regions where wheat is more widely grown (Hutchins, 2019).

While feeding wheat to beef cattle is not a novel concept, much of the previous research was done prior to the widespread use of distillers' grains. It is hypothesized that feeding WDGS in wheat-based diets will mitigate acidosis concerns by decreasing fines and maintaining a more consistently mixed diet and a greater inclusion of WDGS will improve efficiency. Therefore, the objective of this study was to compare dry-rolled corn or 50:50 blend of dry-rolled corn and dry-rolled wheat in diets with either 12 or 30% WDGS (DM-basis) on finishing cattle performance and carcass characteristics.

## Materials and Methods

All procedures used in these experiments were reviewed and approved by the University of Nebraska – Lincoln Institutional Animal Care and Use Committee (IACUC #1776).

### Experimental Design and Procedures

Crossbred steers (n = 320; initial BW = 325 kg; SD = 23 kg) were fed for 158-d at the University of Nebraska – Lincoln Panhandle Research and Extension Center (PHREC) near Scottsbluff, NE. Treatments were arranged in a 2 × 2 factorial design consisting of 2 grain types [dry-rolled corn (**DRC**) or 50:50 dry-rolled corn/dry-rolled wheat blend (**WHEAT**)] and wet distillers' grains inclusion [12% DM-basis (**12WDGS**) or 30% DM-basis (**30WDGS**). Steers were assigned randomly to pen (n = 32; 10 steers/pen) and pen was assigned randomly to treatment, with 8 replications per treatment. Three BW blocks were utilized, with 2 reps in the light block, 4 reps in the middle block, and 2 reps in the heavy block.

Prior to trial initiation, all steers were individually identified and processed at arrival at the research feedlot with a modified live viral vaccine for infectious bovine rhinotracheitis, bovine viral diarrhea types I and II, parainfluenza 3, and bovine respiratory syncytial virus (Bovi-Sheild Gold 5, Zoetis Inc., Kalamazoo, MI), a killed vaccine for clostridial toxoids and *Histophilus somni* (Ultrabac 7/Somubac, Zoetis) and a topical pour-on for the treatment and control of gastrointestinal roundworms, lungworms, grubs, horn flies, sucking and biting lice, and sarcoptic mange mites (Ivermax, Aspen Veterinary Resources, LTD., Greeley, CO). All steers were revaccinated approximately 15 d after initial processing with a modified live viral vaccine for infectious bovine rhinotracheitis, bovine viral diarrhea types I and II, parainfluenza 3, and bovine respiratory syncytial virus (Bovi-Sheild Gold 5, Zoetis). Prior to trial initiation, steers were limit fed (Watson et al., 2013) a diet containing 30% alfalfa hay, 40% corn silage, 25% WDGS, and 5% supplement (DM-basis) at 2% of BW for 7 d to equalize gastrointestinal fill prior to weighing on d 0 and 1 for initial BW determination.

Wheat and corn was processed on site using a roller mill (Automatic Ag, Pender, NE for wheat and Rosekamp Huller Mfg., Co., Cedar Falls, IA for corn). All steers were fed a liquid supplement formulated to provide 33 mg/kg of monensin (Elanco Animal Health, Greenfield, IN) in diet and a targeted intake of 90 mg/steer daily of tylosin (Elanco Animal Health). Urea was provided in the supplement at 0 or 1% of diet DM. Supplement providing 1% urea was used in the DRC/12% WDGS diet and a 50:50 blend of the 0% and 1% urea supplements was used in the corn-wheat blend diet with 12%

WDGS. No urea was provided in the diets containing 30% WDGS. Urea inclusion was determined based on the crude protein (CP) of the diets and wheat having more CP than corn. Both finishing diets with 12% WDGS contained 13.0% CP (DM-basis). The DRC 30WDGS diet contained 14.7% CP, and WHEAT 30WDGS contained 15.7% CP. Steers were implanted with Revalor-XS (200 mg trenbolone acetate + 40 mg estradiol, Merck Animal Health, Summit, NJ) on d 1.

Pens were fed once daily at approximately 0800 h with the goal of trace amounts of feed in the bunk at the time of feeding. Dietary ingredients were sampled weekly for determination of DM and as-fed proportions of ration ingredients were adjusted weekly. Weekly samples were composited by month and sent to a commercial laboratory (Ward Labs, Inc., Kearney, NE) for chemical analysis and nutrient determination. Cattle were adapted to their respective finishing diet over 24 d. Step 1 diets were fed for 4 d and contained (DM-basis) 17% of respective grain, 12% WDGS, 40% corn silage, 25% alfalfa hay, and 6% supplement. Step 2 diets included 27% grain, 12% WDGS, 40% corn silage, 15% alfalfa hay, and 6% supplement and were fed for 6 d. Step 3 diets (7 d) contained 37% grain, 12 or 20% WDGS respective of treatment, 40% corn silage, 5% alfalfa hay, and 6% supplement. Final step-up diets included 52% grain, 12 or 30% WDGS, 30% corn silage, and 6% supplement and were fed for 7 d prior to the finishing rations. The finish rations (Table 2.1) included 49 or 67% respective grain, 12 or 30% WDGS, 15% corn silage, and 6% supplement.

Steers were fed for 158 d and were harvested at a commercial abattoir (Greater Omaha Packing, Omaha, NE). On the day of shipping, pens were fed 50% of the previous day’s offering at regular feeding time. Cattle were loaded in the afternoon and transported for harvest the following morning. Individual pens were weighed on a pen scale (Sooner Scale, Inc., Oklahoma City, OK) prior to being shipped with the pen weight divided by number of animals in the pen to determine final BW for individual animals. A 4% pencil shrink was applied to this live BW to serve as final live BW and calculation for dressing percentage (HCW divided by shrunk live final BW). Hot carcass weight and liver score and severity were obtained the day of harvest and marbling score, $12^{th}$ rib fat thickness, and LM area were collected following a 48-h chill. Calculated yield grade was determined using the following equation (USDA, 2016): 2.50 + (0.98425 × $12^{th}$ rib fat, cm) + (0.2 × 2.5 KPH, %) + 0.00837 × HCW, kg) – (0.0496 × LM area, $cm^2$), where KPH fat was assumed to average 2.5%. Carcass adjusted final BW, and subsequent calculations of carcass-adjusted ADG and G:F, were calculated from HCW divided by a common dressing percent of 63%.

**Particle size analysis**

Samples of processed corn and wheat were taken throughout the trial, composited, and analyzed for particle size using dry sieving. Samples were analyzed as-is to prevent damage to the kernels. Each sample was shaken through a series of sieves for 10 minutes and each individual sieve was weighed to determine amount retained at each individual particle size. Samples were measured in duplicate, and the amount retained on each sieve was used to determine geometric mean diameter and geometric standard deviation using equations derived from ASAE (2008).

*Economic Analysis*

Daily spot bids for yellow corn and hard red winter wheat #1 were collected from local elevators in Scottsbluff and Chase counties in Nebraska and Weld county in

Colorado for 2013 through 2020. Bushel price was converted to price per 909 kg (DM-basis) for both corn and wheat, using a DM of 84.5% for corn and 86.5% for wheat. Bushel weight was assumed to be 25.4 kg for corn and 27.2 kg for wheat. The difference in corn and wheat prices (dry basis) were calculated by day and averaged by month. Differences between corn and wheat prices were compared across years and months and the proportion of months were quantified where wheat was priced equal to or less than corn.

### Statistical Analysis

Animal performance and carcass traits were analyzed as a 2 × 2 factorial arrangement using the MIXED procedure of SAS 9.4 (SAS Institute, Inc., Cary, NC). The model consisted of the fixed effects of block, grain type, WDGS inclusion, and the interaction between grain type and WDGS inclusion. Pen was considered the experimental unit. Appropriate interactions between grain type × WDGS inclusion were tested and removed from the model if not significant. Liver scores were analyzed using the GLIMMIX procedure of SAS using a binomial distribution. Means are calculated using LS means. Alpha values of $\leq 0.05$ were considered significant and $0.05 < \alpha \leq 0.10$ was considered a tendency.

## Results and Discussion

The geometric mean diameter for DRC and WHEAT were 3,814 µm and 2,258 µm, respectively. There were no significant interactions between grain type × WDGS inclusion level ($P \geq 0.21$), suggesting that cattle performance and carcass traits were not impacted differently when wheat replaced up to 50% of corn in a finishing diet. Because of the lack of interaction, the main effects of grain type and WDGS inclusion will be discussed.

*Main effect of grain type*

There were no differences in carcass-adjusted final BW, ADG, DMI, or feed efficiency ($P \geq 0.29$; Table 2.2) between DRC or WHEAT. These data suggest that up to 50% wheat can be fed as the grain portion of the diet without adversely affecting performance. Historically, feeding wheat has been limited to less than 40% of diet DM due to its reputation of causing acidosis in feedlot diets (Lardy and Dhuyvetter, 2016). However, combining rapidly fermenting grains, such as wheat, with slower fermenting grains, such as dry-rolled corn, resulted in a decreased risk of acidosis and improved starch utilization (Lardy and Dhuyvetter, 2016; Kreikemeier et al., 1987). Kreikemeier et al. (1987) demonstrated that cattle fed a combination of wheat and corn were 4.4% more efficient compared to cattle fed wheat or corn alone. Furthermore, Axe et al. (1987) reported that increasing the proportion of wheat relative to high-moisture sorghum decreased DMI, increased gain and improved feed efficiency compared to feeding either grain type alone. Fulton et al. (1979) observed erratic intake patterns and decreased DMI when cattle were fed wheat compared to corn, indicating cattle were experiencing acidosis as wheat was fed at 35 to 90% of diet DM. The current trial did not observe any differences in animal performance or DMI by including wheat at 33.5% of diet DM and the lack of differences suggests that acidosis risks were minimized. As expected from similar animal performance, there were no differences between DRC and WHEAT for HCW or dressing percent ($P \geq 0.53$). Longissimus muscle area was greater ($P = 0.02$) for WHEAT compared to DRC. No differences ($P \geq 0.15$) were observed for $12^{th}$-rib fat or

USDA marbling score between grain types, but with the increase in LM area, WHEAT had an improved calculated yield grade (*P* = 0.04). Axe et al. (1987) showed that replacing high-moisture sorghum with wheat had little effect on dressing percent and quality grade, although the blend of wheat and sorghum had improved values compared to feeding wheat alone. Furthermore, there were no differences (*P* = 0.61) for liver abscess percent between DRC and WHEAT, further suggesting that acidosis was mitigated.

*Main effect of WDGS inclusion*

Feeding 30% WDGS (30WDGS) resulted in 11 kg heavier (*P* = 0.03; Table 2.3) carcass-adjusted final BW compared to 12WDGS. Cattle fed increased concentration of WDGS had 4.1% greater ADG (*P* = 0.03) and were 4.4% more efficient (*P* = 0.05) compared to 12WDGS. Furthermore, feeding 30WDGS increased HCW 6 kg (*P* = 0.03), increased $12^{th}$ rib fat thickness (*P* = 0.02), and therefore, tended (*P* = 0.09) to have poorer calculated yield grade compared to 12WDGS. There were no differences ($P \geq 0.13$) between 30WDGS and 12WDGS for dressing percent, LM area, USDA marbling score, or liver abscess percent.

The performance and carcass weight response to increased WDGS in the diet is consistent and well-documented. Vander Pol et al. (2008) observed quadratic increases in final BW, DMI, ADG, and feed efficiency as WDGS was increased from 0 to 50% diet DM, with 30% WDGS inclusion improving final BW by 36 kg and improving G:F by 13% compared to the control. Similarly, HCW responded quadratically, with the maximum HCW being observed at 30% inclusion of WDGS. The changes observed by Vander Pol et al. (2008) were greater than what was observed in the present study, likely a result of changes in distillers grains production. Corrigan et al. (2009) showed that increasing WDGS from 0 to 40% of diet DM improved final BW, ADG, G:F and HCW and decreased DMI. Finally, in a meta-analysis of nearly 20 feedlot trials, replacing corn at up to 40% of diet DM with WDGS improved performance compared to feeding no WDGS in both yearling and calf-fed systems (Bremer et al., 2011).

*Economic Results*

Price data are reported as the differential between corn and wheat price and a value greater than or equal to zero indicates that wheat may be an economical substitute for corn at that price point. Data are presented in Figure 2.1. From 2013 to 2020, wheat was less than or equal to the price of corn 34, 30, or 48% of the months for Scottsbluff, Chase, and Weld counties, respectively. Historically, the price of crop commodities decreases near new crop harvest (Hutchins, 2019), therefore, wheat prices would be expected to be at the lowest during the summer months while corn price is lower in the fall months. Evaluating the differential between corn and wheat in each county for the months of May through September, the proportion of times when wheat is priced at or lower than the price of corn increases to 40, 39, and 50% of the time for Scottsbluff, Chase, and Weld counties, respectively.

However, in late 2013, 2014, 2015, and 2018, wheat was never priced lower than corn, which is likely due to drought conditions. Geographically, where wheat is commonly grown, drought will have a great impact on wheat compared to corn due to the widespread use of irrigation on corn crops, causing the price of corn to be affected less compared to wheat. Furthermore, the demand of these crops from livestock tends to be high in these areas and is especially noticeable in years where supply is affected by drought. Interestingly, in 2016, wheat was priced lower than corn in May and remained lower priced until Summer of 2017, where corn became cheaper than wheat for Chase and Scottsbluff counties, but not Weld county.

Given no difference in performance between diets containing corn or 50% wheat with 50% corn, simply pricing wheat relative to corn on equal DM basis provides information on when wheat is logical to feed, providing an economic incentive to use wheat over corn. However, it is important to note, when low levels of distillers grains are included in the diet (12WDGS), wheat may have added incentive due to its high CP content compared to corn, potentially decreasing the amount of supplemental protein required.

## Conclusions

Overall, the lack of interaction between grain type and WDGS inclusion for animal performance or carcass characteristics suggest that wheat can replace up to 50% of the grain portion in a finishing diet, regardless of WDGS inclusion, without adverse effects on cattle performance. Furthermore, there was a significant response in carcass-adjusted performance for cattle fed 30% WDGS compared to 12% WDGS, but there was no performance response for grain type. Higher concentrations of WDGS increased HCW and $12^{th}$ rib fat but tended to increase calculated YG compared to feeding 12% WDGS. Historically, wheat has been priced equal to or less than the price of corn 30 to nearly 50% of the time depending on location, and that proportion increases during the summer months. There were minimal effects of replacing up to 50% of corn with wheat, but there was a performance and carcass response to feeding higher levels of WDGS.

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**Table 2.1 Diet composition as percent of diet DM**

| **Grain Type**[1] | **DRC** | **WHEAT** | **DRC** | **WHEAT** |
|---|---|---|---|---|
| **WDGS Incl.** [2] | **12WDGS** | **12WDGS** | **30WDGS** | **30WDGS** |
| Corn | 67 | 33.5 | 49 | 24.5 |
| Wheat[3] | 0 | 33.5 | 0 | 24.5 |
| Wet distillers grains + solubles | 12 | 12 | 30 | 30 |
| Corn Silage | 15 | 15 | 15 | 15 |
| Supplement[4] | 6 | 6 | 6 | 6 |
| Urea[5] | 1.0 | 0.5 | 0 | 0 |
| *Chemical Composition, %* | | | | |
| Diet DM | 69.38 | 70.65 | 59.88 | 60.89 |
| Crude Protein | 13.0 | 13.0 | 14.7 | 15.7 |
| Ca | 0.76 | 0.77 | 0.77 | 0.78 |
| P | 0.30 | 0.35 | 0.43 | 0.47 |

[1] Treatments include 100% dry-rolled corn (DRC) or 50:50 blend of DRC and wheat (WHEAT).

[2] 12WDGS = 12% wet distillers grains (WDGS) inclusion, 30WDGS = 30% WDGS inclusion.

[3]Rolled using Automatic Ag Roller Mill (Pender, NE).

[4]Liquid supplement was 68% DM and formulated to provide: 10.9% calcium, 360 mg/animal daily monensin (Rumensin, Elanco Animal Health), and 90 mg/steer tylosin (Tylan, Elanco Animal Health).

[5] Included in the supplement to provide 0, 0.5, or 1% urea in the diet.

**Table 2.2 Main effect of feeding 100% dry-rolled corn (DRC) or 50:50 blend of dry-rolled corn and dry-rolled wheat (WHEAT) on steer performance and carcass traits**

| ***Item*** | **DRC** | **WHEAT** | **SEM** | ***P*-value** |
|---|---|---|---|---|
| Initial BW | 325 | 325 | 0.3 | 0.95 |
| *Live Performance* | | | | |
| Final BW[1] | 613 | 616 | 3.1 | 0.58 |
| Dressing % | 61.8 | 61.6 | 1.7 | 0.53 |
| *Carcass Adj. Performance*[2] | | | | |
| Final BW | 601 | 602 | 3.4 | 0.84 |
| DMI, kg/d | 10.8 | 11.0 | 0.13 | 0.29 |
| ADG, kg | 1.75 | 1.76 | 0.022 | 0.81 |
| Gain:Feed, kg/kg | 0.162 | 0.159 | 0.0022 | 0.43 |
| *Carcass Characteristics* | | | | |
| HCW, kg | 379 | 379 | 2.2 | 0.84 |
| LM area, $cm^2$ | 84.5 | 87.1 | 0.56 | 0.02 |
| 12th rib fat, cm | 1.32 | 1.27 | 0.030 | 0.36 |
| Marbling Score[3] | 533 | 511 | 10.7 | 0.15 |
| Calculated YG[4] | 3.27 | 3.13 | 0.049 | 0.04 |
| Liver Abscess, % | 13.3 | 14.2 | 3.9 | 0.61 |

[1] Pencil shrunk 4%.
[2] Carcass-adjusted final BW and subsequent performance determined from HCW divided by common dressing percent of 63%.
[3] 400 = small, 500=modest, 600= moderate.
[4] Yield grade =2.50 + (0.98425 × 12th rib fat, cm) + (0.2 × 2.5 KPH, %) + 0.00837 × HCW, kg) – (0.0496 × LM area, $cm^2$), where KPH is assumed to be 2.5%.

**Table 2.3 Main effect of WDGS inclusion on steer performance and carcass characteristics**

| ***WDGS Inclusion***[1] | **12WDGS** | **30WDGS** | **SEM** | ***P*-Value** |
|---|---|---|---|---|
| Initial BW | 325 | 325 | 0.3 | 0.51 |
| *Live Performance* | | | | |
| Final BW[2] | 610 | 619 | 3.1 | 0.06 |
| Dressing % | 61.6 | 61.8 | 1.7 | 0.28 |
| *Carcass Adj. Performance*[3] | | | | |
| Final BW | 596 | 607 | 3.4 | 0.03 |
| DMI, kg/d | 10.9 | 10.9 | 0.13 | 0.93 |
| ADG, kg | 1.72 | 1.79 | 0.022 | 0.03 |
| Gain:Feed, kg/kg | 0.157 | 0.164 | 0.0022 | 0.05 |
| *Carcass Characteristics* | | | | |
| HCW, kg | 376 | 382 | 2.2 | 0.03 |
| LM area, $cm^2$ | 85.2 | 86.5 | 0.58 | 0.13 |
| 12th rib fat, cm | 1.24 | 1.35 | 0.033 | 0.02 |
| Marbling Score[4] | 531 | 513 | 10.7 | 0.24 |
| Calculated YG[5] | 3.14 | 3.26 | 0.049 | 0.09 |
| Liver Abscess, % | 11.3 | 12.7 | 3.5 | 0.42 |

[1]Treatments include 12% (DM-basis; 12WDGS) or 30% (30WDGS) WDGS.
[2] Pencil shrunk 4%.
[3] Carcass-adjusted final BW and subsequent performance determined from HCW divided by common dressing percent of 63%.
[4] 400 = small, 500=modest, 600= moderate.
[5] Yield grade =2.50 + (0.98425 × 12th rib fat, cm) + (0.2 × 2.5 KPH, %) + 0.00837 × HCW, kg) – (0.0496 × LM area, $cm^2$), where KPH is assumed to be 2.5%.

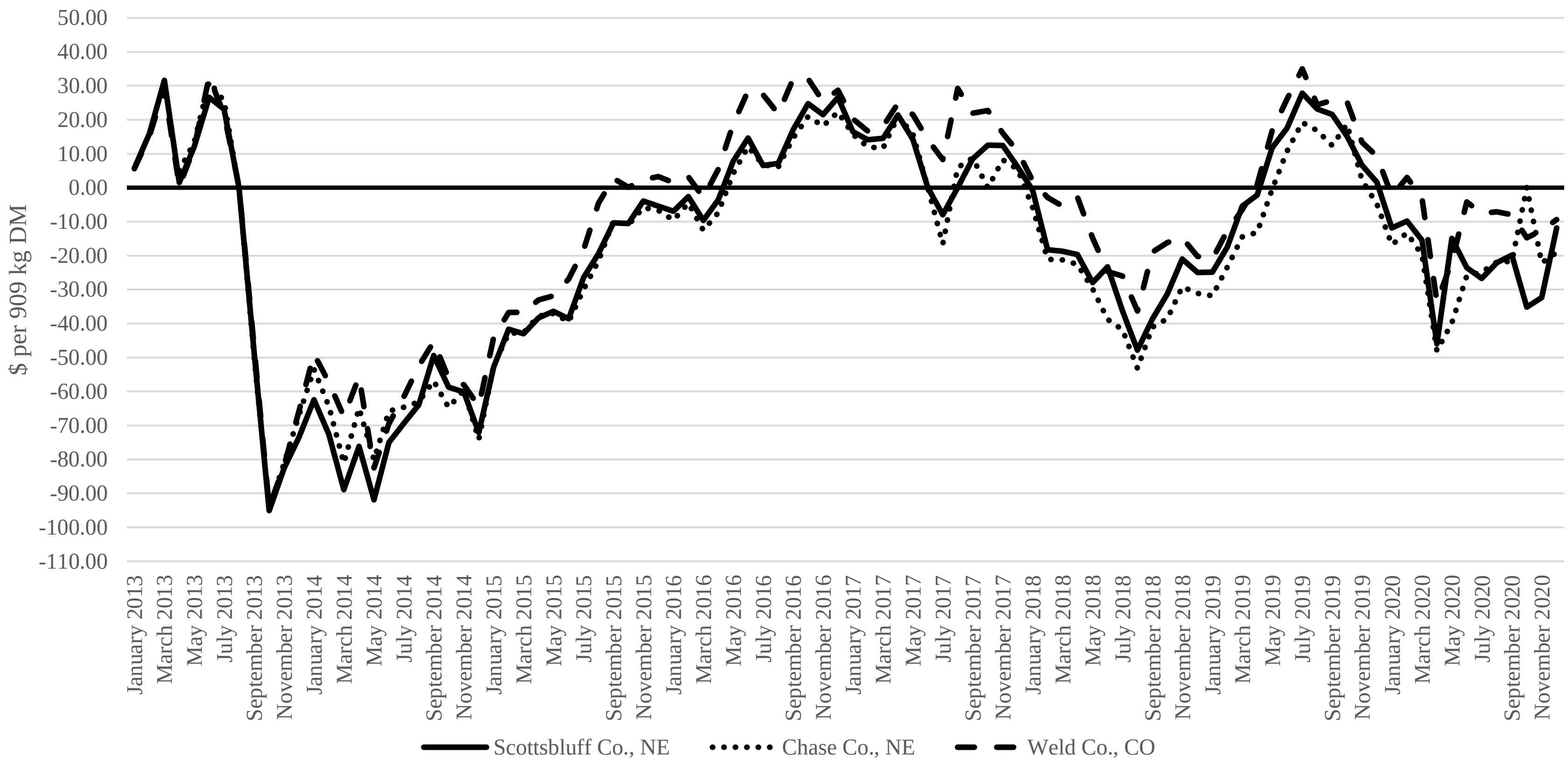


**Figure 2.1** Monthly average of difference between corn and wheat price ($/909 kg DM) for years 2013 to 2020 for Scottsbluff and Chase counties in Nebraska and Weld county in Colorado. A number greater than zero suggests that wheat may be an economical alternative to corn at that price point.

# CHAPTER III. Evaluation of different corn milling methods for high-moisture and dry corn on finishing cattle performance, carcass characteristics, and nutrient digestion.

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## Abstract

Two experiments were conducted to evaluate the effect of different corn milling methods for high-moisture and dry corn on finishing cattle performance, carcass traits, and nutrient digestion. In Exp.1, steers (n = 600; initial BW = 402 ± 17 kg) were fed for134-d to evaluate the effect of milling method and corn type on performance and carcass characteristics. Treatments were evaluated as a 2 × 3 factorial design with factors being milling method [Automatic Ag® roller mill (**ROLL**) or hammer mill (**HAMMER**)] and corn type [high-moisture (**HMC**), dry (**DC**), or 50:50 blend of high-moisture and dry corn (**BLEND**)]. There were no milling method × corn type interactions for final BW, gain (ADG), or dry matter intake (DMI; $P \geq 0.32$), but tended to be an interaction for G:F ($P = 0.09$). Cattle fed ROLL HMC were 4.7% more efficient ($P \leq 0.01$) with 55% lower fecal starch ($P < 0.01$) compared to HAMMER HMC. There were no further effects ($P \geq 0.14$) on performance or carcass traits regardless of milling

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method or corn type. In Exp. 2, 7 ruminally fistulated steers were utilized in a 4 × 7 Latin rectangle to evaluate the effects of DC or HMC processed with either ROLL or HAMMER (2 × 2 factorial treatment design) on nutrient digestion. Feeding HMC decreased the amount of excreted dry matter (DM) and organic matter (OM; $P \leq 0.01$) regardless of mill type, but there was a tendency ($P \leq 0.13$) for an interaction between corn type and mill type for DM and OM digestibility.  There was no difference between milling treatments fed as HMC ($P \geq 0.69$), but the HAMMER DC diet was more digestible than the ROLL DC ($P = 0.05$). As expected, HMC based diets had greater ($P < 0.01$) starch digestibility compared to DC, but milling method had no impact on starch digestibility ($P = 0.56$). There were no differences ($P = 0.56$) in average pH, but HMC diets had greater variance ($P = 0.04$) and greater area under pH 5.6 ($P = 0.05$) compared to DC based diets. Processing HMC with a roller mill improved feed efficiency compared to processing with a hammer mill, but had little effect when corn was fed as dry corn or HMC:DC blend. Furthermore, feeding cattle HMC compared to DC increases nutrient digestibility, but milling method had little impact.

**Key words:** Corn processing, Feedlot cattle, Hammer mill, High-moisture corn, Roller mill, Starch

## Introduction

Historically, the first corn sheller and hammer mill were invented in the 1840s, although commercial cattle feeding did not emerge until the 1940s (Matsushima, 2006). Processing grains is utilized to improve animal efficiency by altering the physical and chemical composition of the grains (Matsushima, 2006). Mechanical processing of grains is achieved by damaging the kernel and reducing particle size for more efficient

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microbial attack in the rumen (Owens and Sonderlund, 2006). For dry and high-moisture corn fed to cattle, a hammer mill or roller mill are the most common methods for processing.

Although both hammer mills and roller mills are sufficient at processing grains, they each have unique advantages and disadvantages. Hammer mills reduce particle size by impacting a slow-moving object, like cereal grains, with a fast-moving hammer. This collision reduces particle size (Koch, 2002). Screens may be used to help dictate maximize size, but the distribution of particle sizes will vary widely around the geometric mean diameter (Koch, 2002). Hammer mills are generally a more cost-effective mill with less expense for maintenance; however, it is less energy efficient than a roller mill and often results in more variable particle size (Koch, 2002). Roller mills decrease particle size through shearing or compression depending on machine-specific design (Koch, 2002). Roller mills are more energy efficient and produce a more uniform particle size compared to hammer mills, but tend to have a higher initial investment with more expensive maintenance (Koch, 2002).

While the literature is extensive regarding grain type, particle size, and processing method, much of the research was done prior to the widespread use of distillers' grains. Therefore, the objectives of these studies were to evaluate the effect of feeding dry, high-moisture, or a blend of high-moisture and dry corn processed with a hammer mill or roller mill in diets containing 20% modified distillers' grains plus solubles on steer performance, carcass characteristics, and nutrient digestion.

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**Materials and Methods**

All procedures used in these experiments were reviewed and approved by the University of Nebraska – Lincoln Institutional Animal Care and Use Committee (IACUC #1785).

**Experimental Design and Procedures: Exp. 1 – Cattle Finishing Experiment**

Crossbred steers (n = 600; initial BW = 389 kg; SD = 17 kg) were utilized in a 134-d finishing trial with a 2 × 3 factorial treatment design. Factors consisted of 2 milling methods [roller mill (**ROLL**; Automatic Ag, Pender, NE) or hammer mill (**HAMMER**; Haybuster, Jamestown, ND for high-moisture corn or Might Giant Tub Grinder, Jones Manufacturing, Beemer, NE for dry corn)] and corn fed one of three ways [100% dry corn (**DC**), 100% high-moisture corn (**HMC**), or a 50:50 blend (**BLEND**)]. Steers were assigned randomly to pen (n = 60; 10 steers/pen) and pen was assigned randomly to treatments, with 10 replications per treatment. Two start blocks were utilized, started 1 wk apart, with 2 BW blocks in the first start block (four reps light block and one rep heavy block) and one BW block in the second start block.

Steers were sourced from auction markets and transported to the University of Nebraska Eastern Nebraska Research and Extension Center (ENREC) located near Mead, NE. At the time of arrival, all steers were individual identified (panel tag, electronic button, and metal clip). All steers received an infectious bovine rhinotracheitis (IBR) virus, parainfluenza-3 ($PI_3$) virus, bovine viral diarrhea (BVD) virus (types I and II), bovine respiratory syncytial virus (BRSV), *Manheimia haemolytica* and *Pasteurella multocida* combination vaccine (Vista Once, Merck Animal Health, DeSoto, KS), a *Clostridium chauvoei, specticum, novyi, sordellii, perfringens* Types B, C, and D

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bacterin-toxoid (Vison 7, Merck Animal Health), a 10 percent fenbendazole oral suspension for the control of lung worms, stomach worms, and intestinal worms (Safe-Guard Dewormer, Merck Animal Health), and one percent doramectin injectable for treatment and prevention of gastrointestinal and external parasite control (Dectomax, Zoetis Inc., Florham Park, NJ).

Before trial initiation, steers were limit fed at 2% of BW for 5 d a diet consisting of 50% Sweet Bran (Cargill Corn Milling, Blair, NE) and 50% alfalfa hay (DM basis) to minimize variation in gastrointestinal fill (Watson et al., 2013). Steers were weighed 2 consecutive days (d 0 and d 1) and averaged to establish initial BW. Steers were blocked by d 0 BW (light or heavy), stratified within BW within blocks and assigned randomly to pen within block. Trial initiation date was also used as a block, with 2 starting dates 1 wk apart and 30 pens starting each week. Pens were assigned randomly to 1 of 6 treatments with 10 pens per treatment.

High-moisture corn was harvested at ENREC in September 2018, processed respective of treatment, and ensiled in plastic-covered bunkers until trial initiation in July 2019. Dry corn was processed on site as needed for both milling methods throughout the trial. Both HMC and DC were processed using a 15.88-mm screen in the hammer mill, and the roller mill was adjusted as needed to ensure all kernels were broken. Corn samples were taken at trial initiation and reimplant for all corns and processing methods for subsequent particle size analysis. Cattle were implanted on d 1 with 80 mg trenbolone acetate (TBA) and 16 mg estradiol (E2; Revalor-IS, Merck Animal Health). Steers were weighed and reimplanted with 200 mg TBA + 20 mg E2 (Revalor-200; Merck Animal Health) on d 50 (84 d on terminal implant). Fecal samples were collected from 2

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steers/pen at reimplant (d 50) and composited wet on an equal volume basis and pen floor fecal samples (n = 2) were collected on approximately d 100 for fecal starch analysis.

Steers were adapted to finishing rations over 23 d with corn replacing alfalfa hay in the step-up diets. All finishing diets included (DM basis; Table 3.1): 70% corn (DC, BLEND, or HMC), 20% MDGS, 5% corn stalks and 5% supplement. The supplement was formulated to target 90 mg/steer tylosin (Tylan; Elanco Animal Health, Greenfield, IN), and 33 mg/kg monensin (Rumensin; Elanco Animal Health), 0.5% diet DM urea, as well as calcium, salt, trace minerals, and vitamins to meet or exceed requirements (NASEM, 2016). Ractopamine hydrochloride (Optaflexx, Elanco Animal Health) was fed for the last 28 d prior to harvest targeting 300 mg/steer. Dietary net energy and metabolizable energy were calculated from animal intake, gain, and BW using equations adapted from the NRC (1996).

Cattle were housed in open feedlot pens with approximately 91 cm of linear bunk space and 56 $m^2$ of pen space per steer. Feed bunks were assessed once daily at approximately 0600 h for the presence of feed, and feed amounts were adjusted to maintain ad libitum access. Cattle were fed once daily between 0700 and 0900 h and had ad libitum access to feed and water for the duration of the trial. Weekly samples of feed ingredients were collected by University personnel, composited by month, and sent to a commercial laboratory (Ward Laboratories Inc., Kearney, NE) for chemical analysis. When refusals were present, orts were weighed, sampled, and frozen for later analysis of DM. Steers were visually evaluated daily, and if a steer was determined to be sick or injured, it was removed from the pen and taken to the processing facility for diagnosis and appropriate treatment prior to being returned to their original pen.

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**Carcass Data**

Cattle were shipped to a commercial abattoir on 2 separate days, 1 wk apart, based on start block. All steers were fed for 134 d. On the day of shipping, steers were offered 50% of the previous day's called feed. Steers were pen weighed in the afternoon prior to shipping and loaded in the evening. All steers were harvested at a commercial abattoir (Greater Omaha Packing, Omaha, NE) the following morning. Hot carcass weights and liver scores were recorded on harvest date and longissimus muscle area, USDA marbling score, and 12$^{th}$ rib fat thickness were collected following a 48-h chill using camera data. Yield grade (USDA, 2016) was calculated from the following formula: 2.50 + (0.98425 × 12$^{th}$ rib fat, cm) + (0.2 × 2.5 KPH, %) + 0.00837 × HCW, kg) – (0.0496 × LM area, cm$^2$). Final live BW and dressing percentage were calculated using the pen average final live BW pencil shrunk 4% to adjust for gut fill. Carcass-adjusted performance was calculated by dividing hot carcass weight by a common dressing percentage of 63%.

**Particle size analysis**

Samples of corn grain from each processing method were taken at time of harvest (HMC), trial initiation, and reimplant. Samples were analyzed wet for particle size (ASAE, 2008) to prevent damage to the kernels, then dried to determine particle size distribution. Samples were measured in duplicate to determine distribution, geometric mean diameter, and geometric standard deviation for each treatment corn.

**Fecal starch analysis**

Animal and pen fecal samples were composited wet on a pen basis and dried using a forced air oven at 60°C for 48 h (AOAC, 1999; method 4.1.03). Dry samples

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were ground through a 1-mm screen for analysis. Ground fecal samples were then analyzed for presence of starch through the hydrolysis of starch granules into D-glucose with α-amylase and amyloglucosidase (Megazyme International Total Starch Assay Kit, AOAC International, 2000; Method 996.11).

**Statistical Analysis: Exp 1**

Animal performance, carcass characteristics, and fecal starch were analyzed as a 2 × 3 factorial arrangement using the MIXED procedure of SAS (SAS Institute, Inc., Cary, NC). The model consisted of the fixed effects of block, corn type, milling method, and their respective interactions. Pen was considered the experimental unit. Interactions between corn type and milling method were tested and if not considered significant ($P > 0.10$), were removed from the model. Interaction of time of fecal sample was also included in the model for fecal starch analysis and removed if not significant ($P > 0.10$). Liver data were analyzed using GLIMMIX as a binomial distribution. Significance was considered at $\alpha \leq 0.05$ and a tendency was considered at $0.05 < \alpha \leq 0.10$.

**Experimental Design and Procedures: Exp. 2 – Cattle Metabolism Experiment**

Seven ruminally fistulated steers were used in a 4 × 7 Latin rectangle, with each steer assigned randomly to each dietary treatment once for 4 consecutive, 21-d periods. Periods allowed for 14 d adaptation, followed by 7 d of collections. Treatment design was a 2 × 2 factorial design, with DC or HMC processed with a roller mill or hammer mill. Steers were fistulated approximately 9 mo. prior to trial initiation. High-moisture and dry corns were the same as utilized in Exp. 1. Diets were mixed twice weekly and stored in a cooler (4°C) to ensure freshness. Experimental diets included (DM basis; Table 3.1): 70% corn, 20% MDGS, 5% corn stalks, and 5% supplement. Supplement was formulated

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to provide 33 mg/kg monensin (Rumensin; Elanco Animal Health), 90 mg/steer daily of tylosin (Tylan; Elanco Animal Health), 0.5% diet DM urea, calcium, salt, trace mineral, and vitamins to meet or exceed requirements (NASEM, 2016). Cattle were adapted to new diets between periods by blending the diet from the previous period and the new period over the course of 5 d. Ingredients were sampled twice during each 21-d period and analyzed for DM using a 60°C forced air oven to ensure proper formulation of treatment diets. Feed refusals were collected from d 16 to 21 and subsampled, DM determined, and intakes were corrected.

Titanium dioxide was ruminally dosed at a rate of 5.0 g/steer twice daily at 0700 and 1700 h for 7 d prior to and for the duration of the collection period. Fecal grab samples (approximately 300 g) were collected d 17 through 21, 3 times daily at 0700, 1300, and 1900 h. Fecal samples were composited by day on a wet basis and freeze-dried (Virtis Feeezemobile 25ES, SP Industries, Warminster, PA). Daily composites were ground to 1-mm and composited by steer within period (equal dry weight by day) to create a period composite sample. Freeze-dried fecal samples were subsequently analyzed for NDF using α-amylase and sodium sulfite (Van Soest et al., 1991), ADF (Van Soest et al., 1991), starch (Megazyme International, AOAC International, 2000; Method 996.11; AACC Method 76.13), and titanium concentration (Spectra MAX 250, Molecular Devices, LLC, Sunnyvale, CA; Meyers et al., 2004). Ruminal pH probes were inserted in the rumen on d 14 and recorded pH data every minute until removal on d 21. Rumen pH data were analyzed for d 16 to 20 to capture collection week and 5 full days of rumen pH measurements. Diet ingredients were also composited into period samples and

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analyzed for DM, OM, NDF, ADF and starch using the same procedures previously described.

**Statistical analysis: Exp. 2**

Total tract nutrient intake and digestion data were analyzed using the MIXED procedure of SAS (SAS Institute, Inc., Cary, NC) with treatment considered a fixed effect and period treated as a random effect. The interaction between corn type and milling method was included in the model and removed if not significant. Ruminal pH data were analyzed using the MIXED procedure of SAS. Day was included as a repeated measure, treatment included as fixed effects, and period included as a random variable. Treatment differences were considered significant when $\alpha \leq 0.05$ and a tendency was considered when $0.05 < \alpha \leq 0.15$.

**Results and Discussion**

Geometric mean diameter (GMD), geometric standard deviation (GSD), and particle size distribution for corns used in Exp. 1 and Exp. 2 are presented in Table 3.2. The GMD for corns processed with ROLL were 3,514 and 2,867 μm for DC and HMC, respectively. The GMD for corns processed with HAMMER were 2,248 and 1,808 μm for DC and HMC. For both DC and HMC, corns processed with HAMMER had more widespread distribution across screens from 600 to 6,300 μm compared to ROLL, which were more closely distributed between 1,700 and 4,750 μm. The average weekly DM across all weeks of the feeding period for ROLL HMC and ROLL DC were 68.2% and 90.0%, respectively, and the average weekly DM of the HAMMER HMC and DC were 65.4% and 89.6%, respectively, for the duration of the feeding periods for both Exp. 1 and Exp. 2.

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**Exp. 1 – Cattle Finishing Experiment**

There were no interactions between corn type × milling method (Table 3.3) for carcass-adjusted final BW, DMI, or ADG ($P \geq 0.32$), but there was a tendency for an interaction between corn type and milling method for feed efficiency ($P = 0.09$). Steers fed the ROLL HMC diet had an improvement in feed efficiency of 4.7% ($P \leq 0.01$) compared to HAMMER HMC. Within corns processed with ROLL, feed efficiency was improved as HMC was increased in the diet, however, a 2.2% decrease in G:F was observed for BLEND, resulting in a negative associate effect ($P < 0.10$) and the interaction. Feed efficiency improved as HMC was added into the diet for HAMMER processed corns, but the increase from BLEND to HMC was less than that observed with ROLL. More extensive processing resulting in smaller particle size, like that observed for processing with HAMMER compared to ROLL, increases starch digestion in the rumen; however, this is not always realized in feedlot performance (Galyean et al., 1981; Schwandt et al., 2016). These results are also similar to Mader et al. (1991) who observed that steers fed rolled HMC (3,965 µm), gained similar to cattle fed whole HMC, but ate significantly less, leading to an improvement in feed efficiency. Ground HMC (3,303 µm) was perceived to be the most digestible but had the poorest feedlot performance. These data suggest that acidosis may be a concern when grains are processed resulting in a small, fine particle size.

The G:F response observed in this study resulted in a tendency for an interaction between corn type and milling method for NEm and metabolizable energy ($P = 0.10$; Table 3.3). The increase in energy from processing grains ultimately improves feed efficiency (Peters, 2006). Like the current study, Macken et al. (2006) observed a 10%

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increase in NEg of corn when fed as rolled high-moisture corn compared to dry-rolled corn; however, only a 5% increase in NEg was observed for corn when fed as ground high-moisture corn compared to fine ground corn. Unsurprisingly, the increase in NEg of the corn was observed in an increase G:F.

There was an interaction (*P* = 0.02; Table 3.3) between milling method and corn type for fecal starch percent. There was little difference in fecal starch percent when corn was fed as DC or BLEND and processed with ROLL or HAMMER. However, fecal starch was reduced by 55% ($P \leq 0.01$) when HMC was processed with ROLL compared to HAMMER HMC resulting in an interaction for fecal starch. There is a close relationship between fecal starch and total tract digestibility in diets that are similar in DM digestibility. Zinn et al. (2002) reported that fecal starch can explain 91% of the variability in starch digestion. Corona et al. (2005) evaluated the relationship between fecal starch and total tract digestibility in feedlot steers and showed the inverse relationship to explain 97% of variability in starch digestion. Vander Pol et al. (2008) concluded that G:F and fecal starch are inversely correlated, and as G:F is decreased, fecal starch is increased. Although the relationship is strong, dietary components, cattle background and genetics, and DMI may all greatly influence nutrient digestibility (Schwandt et al., 2015).

There were no interactions between corn type × milling method for HCW, dressing percent, LM area, $12^{th}$-rib fat thickness, calculated yield grade or liver abscess percent ($P \geq 0.25$; Table 3.3), but there was a tendency for an interaction between corn type and milling method for USDA marbling score (*P* = 0.09) with ROLL BLEND having the greatest USDA marbling score, although the biological reason is unclear. It is

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important to note that there was a high incidence of liver abscesses in this trial suggesting that cattle were challenged from an acidosis perspective as anticipated with a high-concentrate low-roughage diet. However, lack of significant differences across treatments suggest acidosis was not influencing treatment outcomes. Due to the lack of interaction for many variables, main effects of corn type and milling method are presented, aside from feed efficiency as previously discussed.

There were no significant differences in carcass-adjusted final BW or ADG ($P \geq 0.42$) based on corn type (Table 3.4). Cattle fed DC based diet had the greatest DMI ($P < 0.01$), BLEND was intermediate and HMC cattle had the lowest DMI. The differences in DMI are likely due to energy content (HMC being greater than DC) and greater acidosis potential of the HMC. This is consistent with the results of an extensive review from Owens et al. (1997), who reported that more extensive processing of grains decreased DMI and slightly decreased ADG due to excessive rate of acid production in the rumen and subclinical acidosis. However, like the present study, Owens et al. (1997) also observed an improvement in feed efficiency observed with more extensive processing, which supports increased energy with more extensive processing. Vander Pol et al. (2008) also observed a 5.1 and 7.9% decrease in DMI compared to DRC based diets when cattle were fed a 1:1 blend of DRC:HMC or HMC with 30% WDGS. Furthermore, Vander Pol et al. (2008) observed no differences in ADG based on corn processing, thus leading to a 1.6 and 3.2% increase in feed efficiency for cattle fed DRC:HMC or HMC, respectively, compared to DRC alone. Conversely, combination of rapidly fermenting grain and a slower fermenting grain (i.e., dry corn and HMC) has previously been shown to increase gain and feed conversion compared to feeding DC or HMC alone (Stock and

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Erickson, 2006). In this study, BLEND did not improve feed efficiency compared to DC and HMC, resulting in no associative effect. The lack of associative effect is consistent with the work previously discussed by Vander Pol et al. (2008), who observed no associative effect when a 1:1 blend of DRC:HMC was fed compared to DRC or HMC alone. It appears gut fill tended (*P* = 0.07) to increase final live BW for cattle fed dry corn. High-moisture corn diets provided significantly ($P \leq 0.01$) more dietary energy compared to BLEND or DC (Table 3.4), which again, is consistent with the review from Owens et al. (1997), who reported a 5% increase in metabolizable energy for HMC compared to DC. There were no differences due to corn type for HCW, dressing percent, LM area, USDA marbling score, 12$^{th}$ rib fat thickness, or liver abscess percent ($P \geq 0.12$); however, steers fed HMC diets had a lower (*P* = 0.05) calculated YG compared to DC, but these treatments did not differ from BLEND. The lack of differences in HCW is somewhat surprising as an increase in carcass-adjusted final BW, and therefore, HCW, has been consistently reported for DC compared to HMC-based diets (Scott et al., 2003; Vander Pol et al., 2008; Corrigan et al., 2009).

There was no effect on carcass-adjusted final BW, ADG, or DMI based on mill type ($P \geq 0.15$; Table 3.5) Diets processed with the roller mill had greater NEg (*P* = 0.04), and there was a tendency for the roller mill diets to have greater NEm and ME ($P \leq 0.07$) compared to processing with the hammer mill (Table 3.5). In the current study the average particle size for ROLL was 3,191 µm compared to 2,028 µm for HAMMER. Research has consistently shown that decreasing particle size regardless of grain type will increase ruminal starch digestion (Galyean et al., 1981; Schwandt et al., 2016), but not always translate into improved feed efficiency (Mader et al., 1991; Schwandt et al.,

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2016). Processing with a roller mill generally produces particles that are more uniform in size compared to the hammer mill, which, in combination with MDGS, may improve the consistency of the diet and mitigate the risk of subacute acidosis (Koch, 2002; Schwandt et al., 2015; Lundy et al., 2015). Schwandt et al. (2016) also observed no differences in feedlot performance as dry corn particle size was reduced, although *in situ* digestibility was seemingly increased with finer particle size. *In situ* data should be interpreted with caution due to potential inflation of values from problems with washout. There was no effect of milling method on carcass characteristics ($P \geq 0.14$). The lack of differences from milling method are consistent with Schwandt et al. (2016) who observed no differences for any carcass traits measured based on processing method when WDGS was included at 20% of the diet. Furthermore, Swanson et al. (2014) observed no differences in HCW, 12$^{th}$-rib fat, or LM area when corn was rolled as coarse or fine and DDGS was included at 20 or 40% of the diet.

**Exp. 2 – Nutrient Digestion Experiment**

There were no interactions ($P \geq 0.18$; Table 3.6) between corn type and milling method for total tract DM intake, DM excreted, OM intake, OM excreted, NDF digestibility, ADF intake or ADF excretion. There tended to be an interaction ($P = 0.13$) between corn type and milling method for total tract DM digestibility, resulting from a larger improvement in DM digestion for HMC compared to DC when rolled (6.9 percentage units) compared to the increase observed from HMC and DC processed as HAMMER. Organic matter digestibility followed the same trend, with the interaction ($P = 0.10$) occurring due to a more dramatic increase in OM digestion for ROLL HMC than ROLL DC (7.6 percentage units) compared to corns processed with HAMMER (84.5 and

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81.5% for HAMMER HMC and DC, respectively). It has been well documented that the moisture content of grain and the particle size of processed grains largely dictate degree of digestibility, particularly in the rumen (Owens and Sonderlund, 2006). The larger particle size of ROLL DC compared to HAMMER DC (Table 3.2) hinders total tract digestion. The lack of differences between high-moisture corn regardless of processing types is not surprising due to the high digestibility of HMC regardless of processing type. The diet containing ROLL HMC had the greatest ADF digestibility but was not different from HAMMER HMC or HAMMER DC, and ROLL DC had the lowest ADF digestibility; however, is unclear what caused the differences in ADF digestibility. There were no interactions ($P \geq 0.27$) for starch intake, excretion, or digestibility among all treatments. Total gross energy intake (Mcal/d), and therefore total digestible energy intake, was not different ($P \geq 0.34$) among treatments. There was a tendency ($P = 0.13$) for an interaction between corn type × milling method for digestible energy intake per kilogram of DM intake. The HMC diets regardless of processing method had the greatest DEI (Mcal/kg DM), HAMMER DC was intermediate, and ROLL DC had the lowest DEI (Mcal/kg DM). As corn is more extensively processed, through both fermentation and mechanical processing, energy availability is increased (Peters, 2006). Additionally, as the moisture content of grains increase, such as from DC to HMC, metabolizable energy content also increases (Owens et al., 1997). In the current study, the change in energy from DC to HMC was observed; however, HAMMER HMC had a slightly lower DM than ROLL HMC (65.4 and 68.2%, respectively). Although metabolizable energy was not measured, the change in DM between the HMC for HAMMER and ROLL did not

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result in an increase of gross or digestible energy. There was no interaction between corn type and milling method for digestible energy as a percent of gross energy.

**Effect of corn type on nutrient digestion**

There was no effect (*P* = 0.20; Table 3.6) of corn type on DM or OM intake of cattle; however, feeding HMC decreased DM and OM excretion, which increased DM and OM digestion compared to DC. Increased ruminal and total tract digestibility is common with fermented feeds, especially in high-concentrate diets (Owens and Sonderlund, 2006). Although the current study only evaluated total tract digestion, previous research concludes that reduced particle size and fermented feeds had the greatest influence on rumen digestibility through improved rumen fermentation (Hale, 1973; Owens and Sonderlund, 2006). Similarly, cattle consuming HMC based diets had lower NDF intakes (*P* = 0.02) and excreted less (*P* = 0.04), thus having no effect on NDF digestibility (*P* = 0.30). These results agree with the observations of Corrigan et al. (2009), who concluded that cattle fed HMC-based diets consumed less NDF than that of dry-rolled corn-based diets, with no effect on NDF digestibility. There was no difference (*P* = 0.20) between DC and HMC for ADF intake, but ADF excretion decreased slightly (*P* = 0.05) for HMC compared to DC. But the change in excretion did not translate (*P* = 0.16) into increased ADF digestibility for HMC compared to DC. Corn type did not influence (*P* = 0.43) starch intake, but as expected, HMC decreased starch excretion (*P* < 0.01) and improved starch digestion (*P* < 0.01) compared to DC. As previously discussed, it has been well documented that HMC increases total tract starch digestion. High-moisture corn has greater ruminal starch digestibility compared to DC, which means that more starch from DC enters the small intestine (Owens and Sonderlund, 2006;

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Owens and Zinn, 2005). Although a greater amount of starch is digested in the small intestine as a percent of total starch intake in DC-based diets, the starch in HMC is more digestible in the small intestine compared to DC, improving total tract digestibility of starch (Owens and Zinn, 2005). In a review by Huntington (1997), total tract starch digestion was increased from 92.2% when cattle were fed DC to 95.3% when HMC was fed. Cooper et al. (2002) observed an increase in total tract starch digestion when HMC was fed compared to DC (98.7 and 96.1%, respectively), which agrees with results reported by Galyean et al. (1976) where total tract starch digestibility was 96.3% for DC and 99.1% for ground HMC. These results agree with the total tract starch digestibility in the current study, where digestibility was increased from 92.5% for DC to 98.6% for HMC. Interestingly, in the feedlot performance study, HAMMER DC had the greatest fecal starch concentration, which may indicate lower total tract digestibility, which contradicts these nutrient digestion results and from what would be expected with reduced particle size of the HAMMER DC compared to ROLL DC. The inconsistency between fecal starch percent from the pen study and starch digestion values from the current study may indicate that DMI or passage rate may play a role in total tract digestibility in combination with factors previously discussed (Rowe et al., 1999). Total energy intake (Mcal/d), expressed as GE or DE, was unaffected by corn type, but cattle consuming HMC consumed more ($P < 0.01$) energy per kilogram of DM.

**Effect of mill type on nutrient digestion**

Overall, there were no differences ($P \geq 0.18$; Table 3.6) in nutrient digestion between corns processed with ROLL or HAMMER. Data regarding the effect of processing corn with a roller mill or hammer mill are lacking in the literature; however,

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the primary differences in the end of product between the milling methods is particle size and variation across screen sizes. In this trial, reduction in particle size with the hammer mill, regardless of corn type, was not enough to influence nutrient digestibility alone. Furthermore, the literature related to the effect of altering corn particle size in diets containing distiller's grains is limited. However, some evidence suggests that addition of wet distiller's grains in diets containing highly-processed corn, resulting in smaller particle size, is sufficient to improve homogeneity of the diet, bind fines, and possibly dilute readily ruminally-available starch to control acidosis related events (Schwandt et al., 2016). Conversely, Corrigan et al (2009) and Luebbe et al. (2012) showed no effect on ruminal pH parameters compared to a negative control when WDGS displaced rapidly fermenting starch (DRC, HMC, or SFC), suggesting no influence on ruminal acidosis when WDGS displaced starch.

**Effect of corn type and milling method on ruminal pH**

There were no interactions ($P \geq 0.18$; Table 3.7) between corn type × milling method for any pH parameters, with the exception for a tendency ($P = 0.07$) for an interaction of minimum pH. Minimum ruminal pH was the lowest for ROLL HMC but was not different from HAMMER DC and HAMMER HMC. Either HAMMER treatment did not differ from ROLL DC, which had the greatest minimum pH. There was no effect ($P \geq 0.20$) of milling method on any ruminal pH parameters. Corn type had the greatest influence on ruminal pH. Average, minimum, or maximum pH were not influenced ($P \geq 0.34$) by corn type; however, HMC had greater ($P = 0.04$) pH variance compared to DC. With greater variance, it is not surprising that HMC increased the ($P = 0.05$) area (min/d) under pH 5.6 and tended ($P \leq 0.10$) to have greater time and area

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(min/d) under pH 5.3. Observed changes in pH between DC and HMC are consistent with Corrigan et al. (2009), who observed an increase in pH variance and time less than a pH of 5.0 in steers that were fed HMC compared to DC. Moreover, Cooper et al. (2002) observed a significant decrease in ruminal pH in cattle fed HMC compared to DC and remained lower than DC for up to 15 h post feeding, which is inconsistent with the current study (Figure 3.1).

## Conclusions

Feeding cattle HMC processed with a roller mill increased feed efficiency by nearly 5% in the feedlot compared to cattle fed HMC processed with the hammer mill; however, processing method did not influence feedlot performance in dry corn or diets fed as a combination of dry and HMC. Except feed efficiency, there were no other interactions between corn type and milling method for intake, gain, or carcass traits. Feeding cattle HMC improved gain regardless of milling method compared to cattle fed BLEND or DC. Milling method alone had little effect on steer performance or carcass characteristics. Furthermore, the interaction between corn type and milling method may be explained by the observed interaction in OM digestion. As expected, corn type had the greatest influence on nutrient digestibility, with HMC increasing DM, OM, and starch digestibility compared to DC. Feeding HMC had the greatest effect on pH, resulting in greater pH variance, area < 5.6, and time and area < 5.3 compared to DC. There was no influence of milling method alone on nutrient digestion. Overall, processing high-moisture corn with a roller mill improves feed efficiency in finishing diets containing MDGS by 4.7%; however, there is little difference in nutrient digestion between HMC processed with ROLL or HAMMER.

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**Table 3.1. Composition (DM basis) and chemical analysis of diet fed to finishing steers (Exp. 1 and 2)**

| | ROLL | | | HAMMER | | |
|---|---|---|---|---|---|---|
| | **DC** | **BLEND** | **HMC** | **DC** | **BLEND** | **HMC** |
| Dry corn | 70 | 35 | - | 70 | 35 | - |
| High-moisture corn | - | 35 | 70 | - | 35 | 70 |
| Modified Distillers + Solubles | 20 | 20 | 20 | 20 | 20 | 20 |
| Corn Stalks, ground | 5 | 5 | 5 | 5 | 5 | 5 |
| Supplement [1] | | | | | | |
| Fine ground corn | 2.29 | 2.29 | 2.29 | 2.29 | 2.29 | 2.29 |
| Limestone | 1.69 | 1.69 | 1.69 | 1.69 | 1.69 | 1.69 |
| Tallow | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| Urea | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Salt | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Trace Mineral | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| Vitamin A-D-E | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 |
| Rumensin-90 | 0.017 | 0.017 | 0.017 | 0.017 | 0.017 | 0.017 |
| Tylan-40 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 |
| *Chemical Composition* | | | | | | |
| CP, % | 14.55 | 14.62 | 14.69 | 14.63 | 14.62 | 14.62 |
| Ca, % | 0.65 | 0.65 | 0.65 | 0.65 | 0.66 | 0.66 |
| P, % | 0.41 | 0.40 | 0.39 | 0.41 | 0.39 | 0.37 |
| NDF, % | 17.08 | 16.72 | 16.37 | 17.96 | 17.28 | 16.60 |
| ADF, % | 7.40 | 7.56 | 7.72 | 7.28 | 7.44 | 7.61 |
| Starch, % | 52.96 | 52.50 | 52.04 | 52.33 | 52.14 | 51.95 |

[1] Supplement formulated to provide 33 mg/kg monensin (Rumensin, Elanco Animal Health) diet DM, 90 mg/steer daily of tylosin (Tylan, Elanco Animal Health), and trace mineral package.

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**Table 3.2. Particle size distribution by percent retained on screen, geometric mean diameter (GMD) and geometric standard deviation (GSD) for corns fed in Exp. 1 and Exp. 2.**

| | ROLL[1] | | | | HAMMER | | | |
|---|---|---|---|---|---|---|---|---|
| Screen Size, µm | **DC** | **CV[2]** | **HMC** | **CV** | **DC** | **CV** | **HMC** | **CV** |
| 6,300 | 1.7 | 43.8 | 9.7 | 30.0 | 10.9 | 16.9 | 30.1 | 13.1 |
| 4,750 | 29.5 | 17.5 | 34.5 | 9.0 | 8.3 | 6.9 | 18.7 | 14.8 |
| 3,350 | 39.8 | 18.7 | 26.1 | 6.4 | 15.8 | 16.9 | 22.2 | 5.32 |
| 1,700 | 23.8 | 21.6 | 17.3 | 10.9 | 29.0 | 8.2 | 20.9 | 8.9 |
| 1,410 | 1.3 | 77.9 | 2.1 | 28.2 | 11.6 | 5.3 | 2.1 | 44.7 |
| 850 | 1.7 | 93.8 | 3.8 | 27.0 | 8.5 | 7.6 | 2.9 | 57.6 |
| 600 | 0.5 | 117.6 | 2.0 | 42.5 | 5.3 | 21.6 | 1.1 | 89.1 |
| <600 | 1.7 | 117.4 | 4.5 | 32.6 | 10.7 | 25.2 | 1.7 | 78.9 |
| GMD, µm | 3,514 | -- | 2,867 | -- | 1,808 | -- | 2,248 | -- |
| GSD, µm | 1,160 | -- | 1,335 | -- | 924 | -- | 501 | -- |

[1]Treatments were corn processed with a roller mill (ROLL) or hammer mill (HAMMER) and fed as dry corn (DC), 50:50 blend of DC and high-moisture corn (BLEND) or high-moisture corn (HMC).

[2] Coefficient of variance for each screen size within corn type.

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**Table 3.3. Simple effects of milling method and corn type on performance and carcass characteristics of finishing steers (Exp. 1)**

| | Treatment | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ROLL[1] | | | HAMMER | | | | | | | |
| | DC | BLEND | HMC | DC | BLEND | HMC | SEM | Corn Type | Mill Type | Corn x Mill | ROLL vs. HAMMER HMC |
| Initial BW, kg | 402 | 402 | 402 | 403 | 402 | 403 | 0.5 | 0.35 | 0.03 | 0.54 | 0.08 |
| *Live Performance* | | | | | | | | | | | |
| Final BW, kg | 688 | 680 | 680 | 685 | 681 | 678 | 3.4 | 0.07 | 0.65 | 0.83 | 0.58 |
| Dress, % | 61.8 | 62.4 | 62.4 | 62.0 | 62.3 | 61.0 | 2.40 | 0.18 | 0.40 | 0.25 | 0.08 |
| *Carcass-Adj. Performance*[2] | | | | | | | | | | | |
| Final BW, kg | 674 | 672 | 674 | 675 | 672 | 665 | 4.1 | 0.44 | 0.44 | 0.35 | 0.10 |
| DMI, kg/d | 13.0 | 12.7 | 12.0 | 13.1 | 12.7 | 12.1 | 0.13 | <0.01 | 0.46 | 0.86 | 0.46 |
| ADG, kg | 2.04 | 2.03 | 2.04 | 2.04 | 2.03 | 1.96 | 0.032 | 0.42 | 0.32 | 0.32 | 0.07 |
| G:F | 0.157$^{bc}$ | 0.160$^{bc}$ | 0.170$^{a}$ | 0.156$^{c}$ | 0.160$^{bc}$ | 0.162$^{b}$ | 0.0021 | <0.01 | 0.07 | 0.09 | <0.01 |
| NEm, Mcal/kg[3] | 1.86 | 1.89 | 1.99 | 1.85 | 1.89 | 1.92 | 0.018 | <0.01 | 0.07 | 0.10 | <0.01 |
| NEg, Mcal/kg | 1.22 | 1.26 | 1.34 | 1.22 | 1.26 | 1.28 | 0.016 | <0.01 | 0.04 | 0.16 | <0.01 |
| ME, Mcal/kg | 2.80 | 2.83 | 2.95 | 2.79 | 2.83 | 2.87 | 0.021 | <0.01 | 0.06 | 0.10 | <0.01 |
| Fecal Starch, % | 15.9$^{bc}$ | 13.0$^{b}$ | 7.4$^{a}$ | 17.4$^{c}$ | 16.7$^{bc}$ | 16.6$^{bc}$ | 1.40 | <0.01 | <0.01 | 0.02 | <0.01 |
| *Carcass Characteristics* | | | | | | | | | | | |
| HCW, kg | 425 | 424 | 425 | 425 | 424 | 419 | 2.6 | 0.45 | 0.43 | 0.34 | 0.10 |
| LM area, cm$^2$ | 92.3 | 94.2 | 94.8 | 94.2 | 94.8 | 94.2 | 1.10 | 0.29 | 0.46 | 0.31 | 0.52 |
| Marbling score [4] | 484 | 515 | 475 | 488 | 477 | 474 | 10.7 | 0.12 | 0.18 | 0.09 | 0.99 |
| 12$^{th}$ rib fat, cm. | 1.35 | 1.32 | 1.30 | 1.27 | 1.30 | 1.27 | 0.051 | 0.93 | 0.14 | 0.66 | 0.64 |
| Calculated YG [5] | 3.29 | 3.10 | 3.09 | 3.20 | 3.15 | 3.10 | 0.06 | 0.05 | 0.50 | 0.52 | 0.86 |
| Liver Abscess, % | 28.0 | 27.0 | 38.8 | 24.2 | 29.0 | 28.4 | 5.8 | 0.19 | 0.43 | 0.37 | 0.13 |

[a, b, c] Means without common superscripts differ ($P \leq 0.05$).

[1]Treatments were corn processed with a roller mill (ROLL) or hammer mill (HAMMER) and fed as dry corn (DC), 50:50 blend of DC and high-moisture corn (BLEND) or high-moisture corn (HMC).

[2] Calculated from final BW adjusted to a common dressing percent of 63%.

[3] Calculated using ADG, DMI, and final BW using equations adapted from NRC, 1996.

[4] 400 = small, 500 = modest, 600=moderate.

[5] Yield grade = 2.50 + (0.98425 × 12th rib fat, cm) + (0.2 × 2.5 KPH, %) + 0.00837 × HCW, kg) – (0.0496 × LM area, cm$^2$), where KPH is assumed to be 2.5%.

**Table 3.4. Main effect of corn type on steer performance and carcass characteristics (Exp. 1)**

| | DC[1] | BLEND | HMC | SEM | Corn Type P-Value |
|---|---|---|---|---|---|
| Initial BW, kg | 402 | 402 | 402 | 0.35 | 0.35 |
| *Live Performance* | | | | | |
| Final BW, kg | 686 | 681 | 680 | 3.9 | 0.07 |
| Dress, % | 61.9 | 62.2 | 62.1 | 1.9 | 0.18 |
| *Carcass-Adj. Performance* [2] | | | | | |
| Final BW, kg | 675 | 672 | 670 | 3.0 | 0.44 |
| DMI, kg/d | 13.0$^{a}$ | 12.7$^{b}$ | 12.0$^{c}$ | 0.10 | <0.01 |
| ADG, kg | 2.04 | 2.03 | 2.00 | 0.023 | 0.42 |
| NEm, Mcal/kg[3] | 1.86$^{b}$ | 1.89$^{b}$ | 1.96$^{a}$ | 0.012 | <0.01 |
| NEg, Mcal/kg | 1.22$^{c}$ | 1.25$^{b}$ | 1.31$^{a}$ | 0.011 | <0.01 |
| ME, Mcal/kg | 2.79$^{b}$ | 2.83$^{b}$ | 2.91$^{a}$ | 0.015 | <0.01 |
| *Carcass Characteristics* | | | | | |
| HCW, kg | 425 | 424 | 422 | 1.91 | 0.45 |
| LM area, $cm^2$ | 93.1 | 94.6 | 94.4 | 0.77 | 0.29 |
| Marbling score [4] | 486 | 496 | 474 | 7.9 | 0.12 |
| $12^{th}$ rib fat, cm | 1.30 | 1.31 | 1.29 | 0.028 | 0.93 |
| Calculated YG [5] | 3.24$^{b}$ | 3.12$^{ab}$ | 3.09$^{a}$ | 0.048 | 0.05 |
| Liver Abscess, % | 26 | 28 | 33 | 4.0 | 0.19 |

[a, b, c] Means without common superscripts differ ($P \leq 0.05$).

[1] Treatments include 100% dry corn (DC), 50:50 blend of DC and high-moisture corn (BLEND) or 100% high-moisture corn (HMC)

[2] Calculated from final BW adjusted to a common DP of 63%.

[3] Calculated using ADG, DMI, and final BW using equations adapted from NRC, 1996.

[4] 400 = small, 500 = modest, 600=moderate.

[5] Yield grade =2.50 + (0.98425 × 12th rib fat, cm) + (0.2 × 2.5 KPH, %) + 0.00837 × HCW, kg) – (0.0496 × LM area, $cm^2$), where KPH is assumed to be 2.5%.

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**Table 3.5. Main effect of milling method on steer performance and carcass characteristics (Exp. 1)**

| | ROLL[1] | HAMMER | SEM | Mill Type P-Value |
|---|---|---|---|---|
| Initial BW, kg | 401 | 402 | 0.3 | 0.03 |
| *Live Performance* | | | | |
| Final BW, kg | 681 | 680 | 2.1 | 0.65 |
| Dress, % | 62.2 | 62.0 | 1.6 | 0.40 |
| *Carcass-Adj. Performance* [2] | | | | |
| Final BW, kg | 672 | 670 | 2.6 | 0.44 |
| DMI, kg/d | 12.5 | 12.6 | 0.08 | 0.46 |
| ADG, kg | 2.03 | 2.01 | 0.019 | 0.32 |
| NEm, Mcal/kg[3] | 1.92 | 1.89 | 0.010 | 0.07 |
| NEg, Mcal/kg | 1.27 | 1.25 | 0.010 | 0.04 |
| ME, Mcal/kg | 2.86 | 2.83 | 0.012 | 0.06 |
| *Carcass Characteristics* | | | | |
| HCW, kg | 423 | 422 | 1.6 | 0.43 |
| LM area, $cm^2$ | 93.7 | 94.3 | 0.65 | 0.46 |
| Marbling score [4] | 491 | 480 | 6.8 | 0.18 |
| $12^{th}$ rib fat, cm. | 1.32 | 1.28 | 0.025 | 0.14 |
| Calculated YG [5] | 3.16 | 3.15 | 0.041 | 0.50 |
| Liver Abscess, % | 31 | 27 | 4 | 0.43 |

[a, b, c] Means without common superscripts differ ($P \leq 0.05$)

[1] Treatments include corns processed with roller mill (ROLL) or hammer mill (HAMMER)

[2] Calculated from final BW adjusted to a common dressing percent of 63%.

[3] Calculated using ADG, DMI, and final BW using equations adapted from NRC, 1996.

[4] 400 = small, 500 = modest, 600 = moderate.

[5] Yield grade = 2.50 + (0.98425 × 12th rib fat, cm) + (0.2 × 2.5 KPH, %) + 0.00837 × HCW, kg) – (0.0496 × LM area, $cm^2$), where KPH is assumed to be 2.5%.

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**Table 3.6 Effect of milling method and corn type on total tract digestibility of nutrients in diets containing MDGS (Exp. 2)**

| | Treatment[1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | ROLL | | HAMMER | | | *P*-Value[2] | | |
| | DC | HMC | DC | HMC | SEM | Grain | Mill | Int. |
| *Dry Matter* | | | | | | | | |
| Intake, kg/d | 8.87 | 7.86 | 8.77 | 8.18 | 0.646 | 0.20 | 0.85 | 0.74 |
| Excreted, kg/d | 2.13 | 1.29 | 1.77 | 1.36 | 0.232 | <0.01 | 0.47 | 0.31 |
| Digestibility, % | 76.4$^{b}$ | 83.3$^{a}$ | 80.0$^{a}$ | 82.9$^{a}$ | 2.54 | <0.01 | 0.22 | 0.13 |
| *Organic Matter* | | | | | | | | |
| Intake, kg/d | 8.54 | 7.59 | 8.48 | 7.87 | 0.623 | 0.20 | 0.85 | 0.77 |
| Excreted, kg/d | 1.94 | 1.11 | 1.57 | 1.17 | 0.218 | <0.01 | 0.45 | 0.28 |
| Digestibility, % | 77.7$^{c}$ | 85.3$^{a}$ | 81.5$^{b}$ | 84.5$^{ab}$ | 2.39 | <0.01 | 0.26 | 0.10 |
| *NDF* | | | | | | | | |
| Intake, kg/d | 1.71 | 1.27 | 1.65 | 1.52 | 0.115 | 0.02 | 0.42 | 0.18 |
| Excreted, kg/d | 0.81 | 0.54 | 0.68 | 0.54 | 0.092 | 0.04 | 0.45 | 0.51 |
| Digestibility, % | 53.1 | 57.3 | 58.6 | 63.4 | 5.39 | 0.30 | 0.18 | 0.95 |
| *ADF* | | | | | | | | |
| Intake, kg/d | 0.74 | 0.71 | 0.74 | 0.84 | 0.056 | 0.20 | 0.53 | 0.48 |
| Excreted, kg/d | 0.32 | 0.22 | 0.26 | 0.24 | 0.034 | 0.05 | 0.52 | 0.18 |
| Digestibility, % | 56.0$^{b}$ | 69.7$^{a}$ | 63.9$^{ab}$ | 61.6$^{ab}$ | 5.25 | 0.16 | 0.98 | 0.05 |
| *Starch* | | | | | | | | |
| Intake, kg/d | 4.70 | 4.09 | 4.59 | 4.25 | 0.319 | 0.43 | 0.81 | 0.30 |
| Excreted, kg/d | 0.40 | 0.04 | 0.29 | 0.07 | 0.062 | <0.01 | 0.51 | 0.27 |
| Digestibility, % | 91.5 | 99.0 | 93.7 | 98.4 | 1.21 | <0.01 | 0.56 | 0.29 |
| *Energy* | | | | | | | | |
| GE Intake, Mcal/d | 38.15 | 34.70 | 37.73 | 35.94 | 2.817 | 0.34 | 0.88 | 0.76 |
| DE Intake, Mcal/d | 28.70 | 29.25 | 30.41 | 30.25 | 2.687 | 0.92 | 0.50 | 0.86 |
| DEI, Mcal/kg | 3.28$^{b}$ | 3.71$^{a}$ | 3.44$^{b}$ | 3.68$^{a}$ | 0.107 | <0.01 | 0.29 | 0.13 |
| DE, % of GE | 76.3$^{c}$ | 83.9$^{a}$ | 80.0$^{bc}$ | 83.6$^{ab}$ | 2.53 | <0.01 | 0.22 | 0.15 |

[a, b, c] Values without common superscripts differ ($P \leq 0.10$)

[1]Treatments were corn processed with a roller mill (ROLL) or hammer mill (HAMMER) and fed as dry corn (DC) or high-moisture corn (HMC).

[2] Grain = *P*-value associated with the main effect of grain type, Mill = *P*-value associated with main effect of milling method, Int = *P*-value associated with grain × mill.

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**Table 3.7 Effect of milling method and corn type on ruminal pH (Exp. 2)**

| | Treatment[1] | | | | | P-Value[2] | | |
|---|---|---|---|---|---|---|---|---|
| | ROLL | | HAMMER | | | | | |
| | DC | HMC | DC | HMC | SEM | Grain | Mill | Int. |
| DMI, kg/d | 8.87 | 7.86 | 8.77 | 8.18 | 0.646 | 0.20 | 0.85 | 0.74 |
| *Ruminal pH* | | | | | | | | |
| Minimum pH | 5.27[a] | 5.03[b] | 5.08[ab] | 5.15[ab] | 0.106 | 0.34 | 0.39 | 0.07 |
| Maximum pH | 6.46 | 6.55 | 6.39 | 6.45 | 0.159 | 0.58 | 0.51 | 0.93 |
| Average pH | 5.73 | 5.54 | 5.54 | 5.60 | 0.149 | 0.56 | 0.61 | 0.27 |
| pH Variance | 0.082 | 0.141 | 0.096 | 0.110 | 0.0205 | 0.04 | 0.61 | 0.18 |
| Time < 5.6, min/d | 747 | 900 | 853 | 972 | 145.2 | 0.27 | 0.47 | 0.89 |
| Area < 5.6[3] | 156 | 324 | 245 | 390 | 79.6 | 0.05 | 0.33 | 0.88 |
| Time < 5.3, min/d | 231 | 489 | 442 | 629 | 133.5 | 0.10 | 0.20 | 0.79 |
| Area < 5.3[3] | 17 | 110 | 61 | 139 | 47.3 | 0.08 | 0.44 | 0.88 |

[a, b, c] Values without common superscripts differ ($P \leq 0.10$).

[1] Treatments were corn processed with a roller mill (ROLL) or hammer mill (HAMMER) and fed as dry corn (DC) or high-moisture corn (HMC).

[2] Grain = *P*-value associated with the main effect of grain type, Mill = *P*-value associated with main effect of milling method, Int = *P*-value associated with grain × mill.

[3] Area < 5.6 and < 5.3 = ruminal pH units below 5.6 and 5.3.



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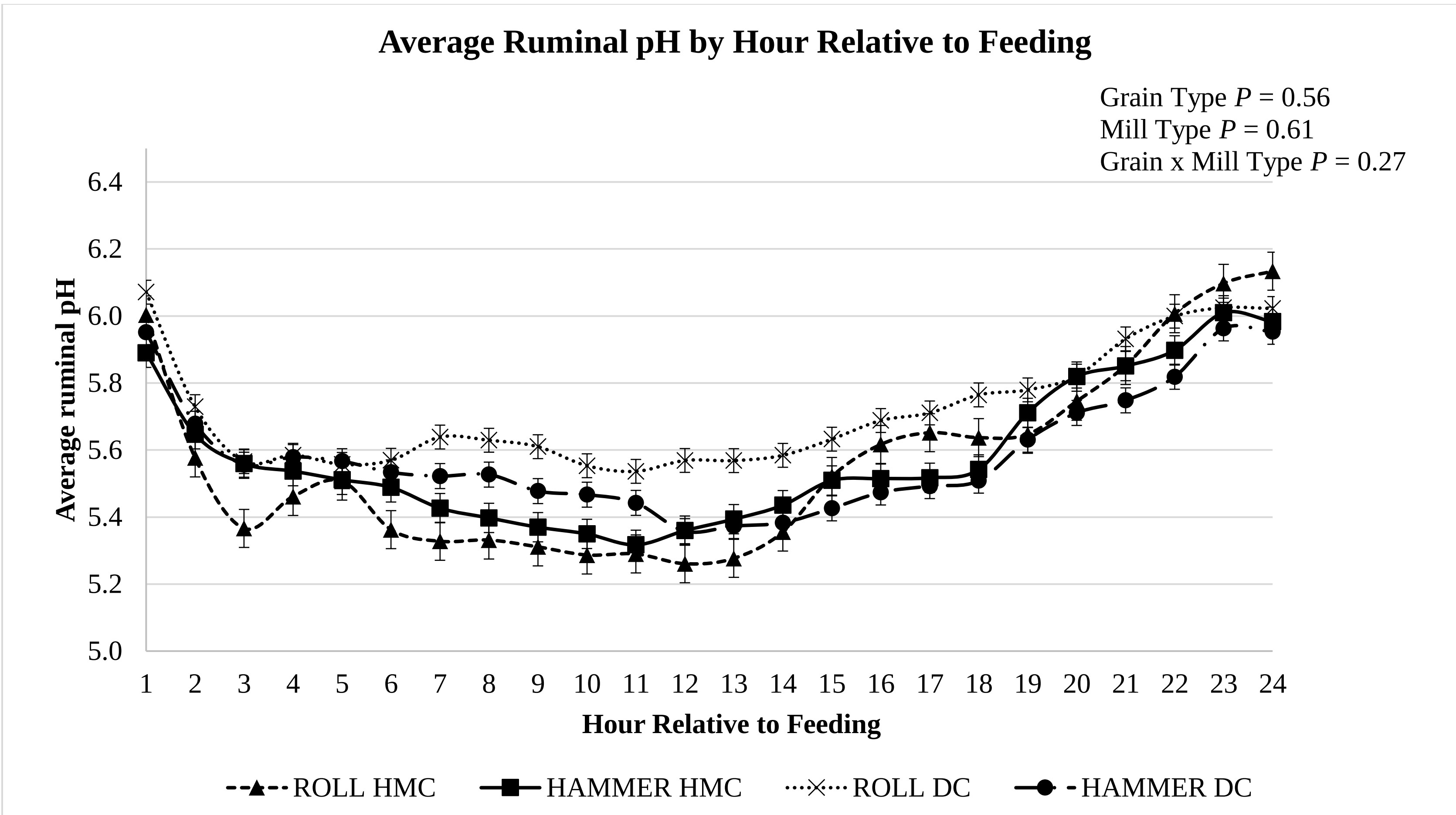


**Figure 3.1.** Average hourly ruminal pH on d 15 through 19 in Exp. 2. Treatments were corn processed with a roller mill (ROLL) or hammer mill (HAMMER) and fed as dry corn (DC) or high-moisture corn (HMC).