EVALUATION OF PERFORMANCE CARCASS CHARACTERISTICS, AND RUMINAL BUFFERING OF FEEDLOT CATTLE CONSUMING DIETS CONTAINING CORN-GRAIN MILLING BYPRODUCTS

by

Paige Rebecca Spowart

B.S. Iowa State University, 2018

A Thesis Submitted in Partial Fulfillment

of the Requirements for the Degree

MASTER OF SCIENCE

Major Subject: Animal Science

West Texas A&M University

Canyon, Texas

August 2020

Approved as to style and contents by:

Dr. Kendall L. Samuelson Chairman, Thesis Committee	Date
Dr. John T. Richeson Member, Thesis Committee	Date
Dr. Ty E. Lawrence Member, Thesis Committee	Date
Dr. Kristin E. Hales Member, Thesis Committee	Date
Head, Major Department	Date
Dean, Academic College	Date
Dean, Graduate School	Date

ABSTRACT

Feeds such as Sweet Bran™ (SB) and wet distillers grains with solubles (WDGS) contribute high concentrations of dietary energy and low starch while potentially providing buffering qualities that may improve rumen health and performance. Feeding combinations of SB and WDGS is common but research is limited. This study evaluated the effects of SB and WDGS in the diet alone or in combination on performance, carcass characteristics, ruminal pH, and rumination time of finishing beef cattle. The study was a randomized complete block design using pen as the experimental unit. Steers (n = 455; 373 ± 15.5 kg) were randomly allocated to 48 pens (12 blocks, 4 pens/block) and transitioned over 20 d to 1 of 4 steam-flaked corn-based dietary treatments containing: no byproducts (CON), 20% WDGS (WDGS), 20% SB (SB), or 20% SB and 10% WDGS (COMBO). Within each pen, 2 steers were randomly selected to receive an indwelling ruminal pH bolus to quantify pH of the rumen and a 3-axis accelerometer tag to measure rumination for the first 92 d of the study. Diet samples were collected weekly to determine particle size, NDF concentration, and physically effective fiber (peNDF). Cattle performance (BW, DMI, ADG, G:F) was not different ($P = 0.96$) through the transition period across all treatments. Overall, final BW, DMI, and ADG were greater ($P < 0.01$) for WDGS, SB, and COMBO than CON. Although overall G:F was not different ($P = 0.48$), feed cost of gain was greatest ($P < 0.01$) for CON, intermediate for WDGS

and SB and least for COMBO. Hot carcass weight was greatest ($P = 0.04$) for SB and WDGS, intermediate for COMBO, and least for CON. A tendency ($P = 0.09$) was observed for yield grade; it was greatest for WDGS, intermediate for SB and COMBO, and lowest for CON. Dressing percentage, marbling score, quality grade, 12th-rib fat, ribeye area, and percentage KPH fat did not differ ($P \geq 0.32$) among treatments. Abscessed livers were not statistically different ($P = 0.27$), but CON had a numerically greater percentage of liver abscesses. The percentage of particles > 4.0 mm was greatest ($P < 0.01$) for CON, intermediate for SB, and least for WDGS and COMBO. However, NDF ($P < 0.01$) and peNDF ($P < 0.01$) were greatest for COMBO, intermediate for WDGS and SB, and least for CON. A treatment × day interaction ($P < 0.01$) was observed for daily rumination minutes per kg of DMI, NDF, and peNDF. A treatment × h interaction ($P < 0.01$) was observed such that CON cattle spent less time ruminating at 0800 and 1000 h in a 24 h period. Ruminal pH was greatest ($P < 0.01$) for COMBO, intermediate for SB and WDGS, and least for CON, but SB did not differ from COMBO or WDGS. Ruminal pH was least ($P < 0.01$) for CON from 0800 to 1800 h. Addition of WDGS and/or SB improved performance and reduced feed cost of gain when incorporated into steam-flaked corn-based finishing diets. Relationships between peNDF, rumination behavior, and ruminal pH suggest that SB and WDGS similarly enhance buffering capacity when steam-flaked corn is replaced in the diet.

ACKNOWLEDGMENTS

First, Holy Father, my relationship with you has grown forever stronger with you as my light during this humbling experience. One of my angels had prayed for patience as many times I felt I had received my ultimate test which I would not pass, but continued to carry on with your spirit in my heart. Although challenging, I am thankful for your gracious gift which has led me from Iowa to the Panhandle of Texas where I found an extension of my family I never knew I needed.

To my adviser Dr. Samuelson: These past two years have been the greatest and I sincerely feel privileged to have been a part of your research group here at WTAMU. I stand taller now because you continuously pushed me out of my comfort zone to meet expectations that I can confidently apply to my everyday life. You always have words of encouragement to pick me up whenever I was feeling tired and defeated plus your compassion and excitement are contagious. As I start my new career, your life lessons will never be forgotten.

To Dr. Richeson: I'm eternally grateful for your unselfish help, patience and advice. I attribute much of my professional development I have gained during my time at WT to you. Your open door policy was greatly appreciated when I needed someone to talk to whenever I hit a road block. Thanks for sharing great memories I will never forget and for always being a great role model.

Sincerest thanks to the faculty, staff, and alumni of WT, for always lending a listening ear, helping with a difficult analysis, providing words of wisdom, or cracking a joke on a rainy day. Specifically, thank you to Dr. Lawrence and Dr. Hales for being dedicated members of my thesis committee. Your kindness and expertise both contributed immensely to my professional development which I will always remember while working alongside you as a member of the agriculture industry.

I owe a huge thank you to the team at the WTAMU Research Feedlot. None of this would be possible without your commitment, dedication, and leadership. There are many hard days and long hours spent at the yard, but we always figured out a solution. Thank you for always standing beside me and also teaching me skills that are not found in a classroom.

To my fellow graduate students: Completing a master's degree is a journey that should not be traveled alone and I am blessed to say I was everything but alone. Thank you to the students, which I can gratefully call my friends, who took me under their wing when I first moved to Texas and integrated me into the WT family. Although we may not all live in Canyon, Texas, the world still got a little smaller.

To my family: Thank you for unconditionally loving me from afar. Each phone call was a cherished moment and I miss you all every day. You share the same excitement for each accomplishment I share with you and are the foundation of my core values and aspirations. Everything I strive to be is with you all in mind. Thanks for being the role models you are and raising me right!

Lastly to Cameron: Thank you for always supporting and bearing a lot of the weight of my day. You provide a safe haven for me to come home to everyday and you always understood the multiple late nights at school. I cannot express to you enough how thankful I am for you being someone who listens, the countless favors, and the graduate suite picnics.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter I: Literature Review

INTRODUCTION

Feeding cattle involves a combination of formulating a diet to meet the nutritional requirements of both the ruminant and the rumen microbial population and optimizing animal management. The goal is to provide sufficient levels of protein and energy to the animal to be converted to beef. In recent years, corn-based cattle diets have become more expensive as grain demand and competition pressure has increased, due to the increase in ethanol and artificial sweetener production for the purpose of human use. This has created an opportunity to evaluate and use alternative feedstuffs, such as grain-milling byproducts, to reduce the cost of cattle diets because feed associated costs are the greatest input cost to a feedlot.

Byproducts are considered organic waste materials from the production of plant-based, human consumables such as meals, distillers grains, or gluten feed. However, these byproducts still have significant nutritional value and can be marketed to beef, dairy, swine, and poultry producers as animal feed ingredients. Currently, distillers grains with solubles are the primary byproduct used to feed cattle in the US, followed by corn gluten feed. In a recent survey of consulting nutritionists completed by Samuelson et al. (2016), 70.8, 16.7, 8.33, and 4.17% of the nutritionists surveyed indicated that they were using either wet distillers grains with solubles (WDGS), dry distillers grains with solubles

(DDGS), wet corn gluten feed (WCGF), or dry corn gluten feed (DCGF) in feedlot cattle diets, respectively. More recently the use of Sweet Bran™ (Cargill Branded Feeds, Blair, NE), a novel blend/alternative of WCGF, has also become popular in feedlot cattle diets because of its availability and consistent quality. Initially, products such as WCGF and WDGS were considered to be an alternative protein source, but these ingredients can also be used as an additional source of energy in place of more expensive processed grains in feedlot cattle diets and are cost competitive (Samuelson et al., 2016). Including byproducts as a component of finishing cattle diets also improves cattle performance and carcass characteristics (Parsons et al., 2007; Kroger et al., 2010) compared to cattle consuming diets with no byproducts. Both WCGF and WDGS are composed of minimal amounts of starch as the available energy is instead provided by high concentrations of slowly-fermentable, non-lignified fiber (Galyean and Hubbert, 2014) which may mitigate acidosis (Krehbiel et al., 1995).

Fibrous feed ingredients are essential components of ruminant diets because fiber particle size > 4.0 mm stimulates ruminal contractions (Mertens et al., 1997; Gentry et al., 2016). Rumen motility (contractions of the rumen) is important to constantly mix the rumen contents for inoculation of feed particles with ruminal microbes, eructation and rumination, and promote passage of digesta into the omasum. The larger particle size provided by roughage will also promote greater time spent ruminating (Gentry et al., 2016) which directly increases salivary secretions (Allen, 1997). When combined, these factors may influence digestibility by increasing ruminal pH or promoting growth of fibrolytic microbial species and overall rumen health.

There is an abundance of information relating fiber characteristics to ruminal health and performance of dairy animals. However, this information is difficult to translate to beef cattle because there are different performance goals and energy requirements between the two industries. The purpose of the following chapters are to characterize both WCGF and WDGS as valuable feed ingredients to improve feed efficiency and rumen health when included in beef feedlot cattle diets. Topics highlighted in this literature review will include the dry and wet milling manufacturing processes used to create grain-milling byproducts, nutritional properties of the various end-products, relationships between diets containing byproducts, finishing cattle performance and carcass characteristics, and rumen buffering potential of cattle diets containing corn-milling byproducts.

MANUFACTURING & NUTRIENT COMPOSITION OF CORN-MILLING BYPRODUCTS

Corn Gluten Feed

In contrast to distillers grains, WCGF is manufactured from the wet milling of grains, which is commonly used to produce artificial sweeteners such as high fructose corn syrup. To begin the wet milling process, grade #1 or #2 shelled corn (Stock et al., 2000) is cleaned of field debris such as sticks and weeds and moved into drums to begin steeping. The corn is then steeped for 40 to 48 h in 50 ℃ water that contains 0.1% sulfur dioxide to break down the internal structures of the kernel, including the endosperm

(starch and protein) and germ (oil). The kernel will also begin to absorb the steep water and swell to contain approximately 45% moisture. The steep water (liquor) is later drained and condensed (condensed fermented corn extractives) to capture nutrients that may have purged from the kernel. Condensed fermented corn extractives are produced from the partial condensation of steep water followed by fermentation by lactic-acid producing microorganisms (AAFCO, 1996).

After separation of the condensed fermented corn extractives, the remaining material (commonly called corn mash) is ground to separate the hulls and endosperm from the germ. The germ can then be processed into corn oil and germ meal. Corn germ meal is ground corn germ which contains little solubles or oil as those components have already been removed by a preceding manufacturing step (AAFCO, 1996). The separated endosperm and hull slurry are crushed using an impactor to separate the endosperm from the fibrous hull. Hulls are passed through a fine-concaved screen that allows any starch and protein to pass and are removed. Hulls (corn bran) are washed again to remove residual starches and protein to capture lost nutrients. Corn bran is the outer hull of the corn that has been washed and contains little or no residual starch (AAFCO, 1996).

The starch and gluten slurry (commonly referred to as mill starch) is then centrifuged using hydrocyclones. Gluten separates from the starch because gluten has a lower density than starch. Corn gluten meal is the dried remainder of the corn grain after starch and oil has been removed and primarily consists of gluten (AAFCO, 1996). Today, there is very little corn gluten meal in corn gluten feed (Stock et al., 2000). The separated starch is then diluted and washed 8 to 14 times until 99.5% pure. This starch can be

processed into syrup, sweeteners, or other fermented products (Corn Refiners Association Inc., 1989). One bushel of corn will produce 0.78 kg corn oil, 1.16 kg gluten meal, 2.67 kg gluten feed, 0.83 kg germ meal, 1.55 kg condensed fermented corn extractives, and 14.64 kg starch and nutritive sweeteners (Blasi et al., 2001).

Corn gluten feed is the product that remains after a large portion of starch, protein, and oil have been removed (AAFCO, 1996). Corn gluten feed is composed of two fractions: corn bran and steep liquor. To manufacture WCGF, first wet corn bran is pressed to a consistent 40% DM concentration and is then combined with corn steep liquor, raising the final DM to 40 to 50%. Similarly, DCGF is created by combining corn bran and corn steep liquor but is then dried in a rotary drum dryer. The dried ingredients are reduced by a hammer mill and fine particles are pelleted to improve commodity management and increase bulk density (Corn Refiners Association Inc., 1989). The nutritional composition of WCGF and DCGF as compared to steam-flaked corn is summarized in Table 1.

During the wet milling process, starch and oil is extracted or fermented and results as an end product that contains very little starch or oil. The remaining fraction is the fibrous hull or corn bran (38.53% neutral detergent fiber and 11.78% acid detergent fiber). The steep liquor is then added back to the corn bran, to use the protein and starch molecules that seeped from the grain while soaking and to take advantage of lost nutrients captured in the water. Corn steep liquor is a good source of rumen degradable protein (RDP) for microbial utilization (Montgomery et al., 2004). Crude protein concentration of the final WCGF or DCGF product depends on the amount of steep

liquor that is added back to the corn bran and will vary based on the production plant's protocol. Final crude protein will vary around 20% of DM (Stock et al., 2000). The final product is a highly fermentable, fibrous ingredient (Blasi et al., 2001) that has a similar energy value when compared to processed corn (Ham et al., 1995; Table 1).

Corn Distillers Grains with Solubles

Distillers grains are a byproduct of the dry milling process used for ethanol production from cereal grains. Corn grain accounts for 95% of the U.S. fuel ethanol supply and is the top yielding grain process (Solomon et al., 2007). Although corn distillers grains is the most prominent byproduct, there is a plethora of grain options and combinations available on the market including milo, wheat, rice, and barley (Solomon et al., 2007). Additionally, some ethanol plants may use a blend of different grains for ethanol production due to market prices at the time of purchase or commodity availability. These grains are highly concentrated with starch molecules, which is the glucose storage form of plants that are more readily available for the fermentation process in comparison to other storage forms of energy such as cellulose (Solomon et al., 2007). After the production of ethanol is complete, the remaining distillers grains can then be manufactured into products such as WDGS, modified distillers grains with solubles (MDGS), and DDGS.

As summarized by Winkler-Moser and Breyer (2011), the dry milling process begins when grains are directed through screens to remove debris. The grain is then

milled into flour and conveyed to slurry tanks. The flour is combined with recycled water and cooked at high temperatures in slurry tanks to break down the grain structure and make the starch more available. Enzymes, yeast, and antibiotics are then added to the resulting mash. Enzymes, such as α-amylase and glucoamylase (Sharma et al., 2007), help further degrade starch molecules into smaller monosaccharide and disaccharide units which allows yeast to thrive and ferment the mash by converting plant sugars to carbon dioxide (CO_2) and alcohol (OH). Antibiotics, such as virginiamycin and penicillin (Connolly, 1999; Lushia and Heist, 2005), are included to decrease growth of competitive bacterial species to promote greater ethanol yield (Chang et al., 1995), and limits the amount of acid producing bacteria present in the mash to control lactic acid and acetic acid production (Makanjuola et al., 1992). After the starch is fermented by the yeast, only the oil, protein, ash, and fiber portions of the kernel remain. The distillation process will then occur by first boiling off 100% pure water at high temperatures, which can then be recycled back to the slurry tanks as described previously. The remaining mash is then processed through distillation columns to increase the ethanol yield per bushel (Stock et al., 2000). After this is completed, the resulting whole stillage contains the remaining non-fermentable solids that will be separated by centrifugation and processed into wet distillers grain and thin stillage. Condensed distillers solubles are evaporated from thin stillage and create a syrup-like product that can either be sold independently or added back into wet distillers grains to produce WDGS or DDGS (Stock et al., 2000). Corn oil can also be extracted from the condensed distillers solubles through an additional centrifugation step and marketed as an additional source of fat and energy in feedlot

diets. One bushel of corn will produce 7.26 kg of dried distillers grain and 10.03 L of ethanol (Dien et al., 2002).

As distillers grains are manufactured, the nutrients become highly concentrated compared to the original grain (Klopfenstein, 1996) because the starch fraction is removed from the feed, leaving behind primarily the protein and oil (Stock et al., 2000). However, the nutrient content also varies with the standard operating procedures used by each production plant, and depends upon the water and oil content of the final product as some ethanol plants may remove a greater proportion of water or extract more oil from the solubles before they are added back to the grain. Table 2 describes the three common variations of distillers grains and the differing oil levels of each product.

Wet distillers grains with solubles is approximately 31% dry matter (DM). Because there is more moisture within this product than DDGS, transportation costs are higher and there is greater potential for spoilage if the product is not stored correctly or used quickly (Klopfenstein, 1996). In contrast, MDGS contain 48% DM and have a storage life intermittent to WDGS and DDGS. Dried distillers grains with solubles are 90% DM and are usually more expensive than WDGS or MDGS because of the added cost of drying (Iowa Beef Center, 2014). Furthermore, as moisture is removed there is more available DM per unit of weight, which will also increase the price of DDGS in comparison to WDGS on an as-fed basis. In addition to changes in DM concentration, the various forms of distillers grains can also be manipulated by extraction of oil. This has become increasingly common in recent years as an attempt to maximize the amount of saleable goods that can be produced from the grains during ethanol manufacturing.

However, increased amount of fat extracted will result in lower fat and energy concentrations of the final distillers product and also presents an additional source of nutrient variation that must be considered when formulating diets.

All forms of distillers grains are high in crude protein and provide a good source of rumen undegradable protein, which describes the protein fraction that largely escapes rumen degradation by microbes and is predominantly digested and absorbed by the small intestine (Klopfenstein, 1996). This provides an important source of amino acids to the animal. Protein concentrations are similar among the various forms of distillers grains and protein quality is affected only slightly during the drying process (Klopfenstein, 1996; Nuttleman et al., 2011) because of the Maillard reaction caused when amino acids and carbohydrates are bound together at high temperatures that occur during the drying process (Ellis, 1959). Another important consideration when feeding ethanol byproducts such as WDGS, MDGS, and DDGS is the high concentration of dietary S commonly present within these ingredients. During the process of converting starches to ethanol, sulfuric acid is added to the mash to control pH, which ultimately transfers to the ethanol byproducts. As S increases in the diet, lower DMI and ADG are observed in comparison to diets formulated to include less S (Sarturi et al., 2013). Wet distillers grains with solubles will typically contain S concentrations of approximately 0.79% on a DM basis, which introduces the potential for ruminants to experience S toxicity (Vanness et al., 2009). When high concentrations of S are fed to ruminants, excess of the ruminal metabolite, hydrogen sulfate (H_2S) present in the blood stream may cause polioencephalomalacia (PEM) or necrosis of the cerebral cortex. Polioencephalomalacia

in cattle causes symptoms such as blindness, ataxia, or seizures, and can ultimately result in death of the animal (Gould, 1998). Cattle fed high concentrate diets are most sensitive to dietary S, and symptoms of PEM have been reported to initiate when S concentrations surpass 0.5% of dietary DM (Nichols et al., 2013). This suggests that the inclusion rate of WDGS should not be greater than 50% on a DM basis to avoid PEM and mitigate S toxicity (Vanness et al., 2009). However, the National Research Council (2005) suggests a maximum S inclusion rate of 0.35% on a DM basis should be used for diets including 15% or less forage and 0.50% on a DM basis for diets including 40% forage or less. Therefore, increasing the concentration of fiber in the diet may allow for greater inclusion of distillers grains and S concentrations (Drewnoski et al., 2014) because increased dietary NDF decreases ruminal H_2S production (Morine et al., 2014). Currently, there is continuing research to explore alternatives to sulfuric acid, such as phosphoric acid, for ethanol production which may help to mitigate some of the negative effects associated with high S in these feedstuffs.

PERFORMANCE AND CARCASS CHARACTERISTICS OF CATTLE CONSUMING CORN-MILLING BYPRODUCTS

There is a large body of research that investigates the effects of byproducts on cattle performance and carcass characteristics against a negative control diet containing no byproducts. However, all nutritionists do not think alike when formulating experimental diets and ingredient selection and inclusion rate can be influenced by region, budget, or personal bias. Variation in the diet formulations used for this research

creates difficulty when drawing absolute conclusions regarding the use of byproducts in feedlot cattle diets. In particular, different corn processing methods, roughage source and concentration, and variations in other nutrients such as dietary fat, energy, and protein concentrations may complicate comparison amongst research studies.

The net energy value of corn increases with a greater degree of processing such that steam-flaked corn (SFC) has greater energy in comparison to high-moisture corn (HMC) and dry rolled corn (DRC; Corrigan et al., 2009). Similarly, less carbon is lost as CH_4 when feeding SFC based diets in comparison to DRC based diets, indicating more carbon is retained by the animal to be used for volatile fatty acid (VFA) synthesis and subsequently, energy (Hales et al., 2012). Therefore, the dietary energy contribution from byproducts may be less when used as a grain replacement in SFC diets in comparison to DRC and HMC. For example, in a study completed by Corrigan et al. (2009), cattle performance is increased by a greater magnitude when cattle are fed WDGS and DRC compared to WDGS and SFC, which indicates SFC has greater energy value in comparision to DRC (Corrigan et al., 2009). These results were not observed in a similar sorghum study conducted by Leibovich et al. (2009) which may be because sorghum has a lower energy value when compared to corn WDGS (Lodge et al., 1997).

Differences in the concentration and source of roughage used in byproduct research may also be another reason for conflicting results reported in the literature. The characterization of roughage is primarily dependent on the composition of soluble and insoluble but fermentable material, rate of degradation, and rate of particle size reduction (Orskov, 1989). However, until recently much of the research investigating the use and

classification of roughage in total mixed rations and its application to ruminal functionality has been focused on dairy cattle. Although, dairy cattle are similar to beef cattle, the dietary management and production goals between the two industries are very different. When feeding diets that contain WCGF, Parsons et al. (2007) indicated that diets including 4.5 to 9.0% alfalfa hay increased ADG. In contrast, May et al. (2011) evaluated different inclusion levels of alfalfa hay when formulated in a WDGS diet and concluded alfalfa inclusion rate is optimal at 7.5% when feeding a diet that contains 15 to 30% WDGS. Work completed by Quinn et al. (2011) suggested that alfalfa hay decreases ADG and subsequently, final body weight (BW), and hot carcass weight (HCW) in comparison to lower quality roughage such as bermudagrass hay or sorghum silage when fed in 15% WDGS diets. Recent research by Gentry et al. (2016), Weiss et al. (2017), and Jennings et al. (2020) indicated that the physical characteristics of the roughage source plays an important role in feedlot cattle diets and warrants further investigation.

Corn Gluten Feed

The results described in the literature when using WCGF are far less variable than those reported for WDGS and generally indicate replacing corn in the diet with WCGF is an advantageous feeding management strategy. Data reported by Block et al. (2005) suggests formulating WCGF at 17-23% (Block et al., 2005) of the diet maximize performance. However, there is little to no benefit observed with WCGF concentrations greater than 40% of DM (Parsons et al., 2007). In contrast, as the inclusion of WCGF exceeds 50% of DM, dry matter intake (DMI) and average daily gain (ADG) begin to

decrease (Hussein and Berger, 1995), likely due to an overall lower energy content of the diet as processed grains are replaced in greater proportions. Generally, DMI of feedlot cattle is greater when WCGF is included in a finishing diet (Macken et al., 2004; Block et al., 2005; Parsons et al., 2007) in comparison to cattle that are fed no byproducts. It is possible that the greater DMI reported by many of these researchers is an effort for cattle to compensate for the slightly lower energy concentrations present in WCGF (Block et al., 2005) and consume similar concentrations of dietary energy as counterparts fed corn-based diets. Interestingly, the published literature also suggests that ADG increases with inclusion of WCGF (Block et al., 2005; Parsons et al., 2007), suggesting that either the greater DMI of cattle consuming WCGF is sufficient to overcome a lower dietary energy density, and/or these feedstuffs are contributing associative effects that optimize rumen fermentation and/or digestion of nutrients. This has also been supported by Block et al. (2005) who concluded that the increased DMI observed in his work was not enough to explain the greater ADG alone. This result has ultimately led some researchers to conclude that byproducts such as WCGF have a greater energy value than corn (particularly dry-rolled), which has been a source of much debate among feedlot nutritionists in recent years. Firkins et al. (1985) and Ham et al. (1995) did not report the same effects for DCGF, where steers also had lower DMI but ADG and final BW were not different, suggesting that using WCGF may be more beneficial in feedlot cattle diets than DCGF. Interestingly, despite greater DMI with the reported enhancements in ADG, G:F ratio does not change (Ham et al., 1995; Macken et al., 2004; Block et al., 2005) implying the positive contribution of WCGF is similar for both DMI and ADG. When

discussing changes in carcass characteristics for cattle consuming WCGF compared to no byproducts, the results explained by previous research suggest that the impact of replacing corn in the diet is more variable on carcass characteristics than on animal performance. Greater HCW has been observed when diets include WCGF in multiple studies (Parsons et al., 2007; Loza et al., 2010; Domby et al., 2010). However, the results described by Macken et al. (2004) suggest that HCW and other carcass characteristics were not different for cattle fed diets containing 10 to 35% WCGF when compared to a control diet that did not include WCGF. Firkins et al. (1985) also reported that increasing WCGF inclusion rate up to 90% did not improve HCW. When they are associated with heavier carcasses, carcass characeristics such as 12th-rib fat thickness and yield grade increase as WCGF is used in the diet (Scott et al., 2003; Domby et al., 2014). Other carcass variables such as marbling score, quality grade, and LM area indicated no effect was associated with including WCGF in the diet as a replacement for corn (Macken et al., 2004; Block et al., 2005). These studies suggest that performance and carcass characteristics of finishing cattle may be maximized when less than 40% WCGF is included in the diet.

Corn Distillers Grains with Solubles

The results reported for finishing cattle performance when increasing the concentration of WDGS in the diet have been highly variable across studies. As previously mentioned, this is likely a function of differences in diet formulations and/or fluctations in the nutrient composition of the WDGS used for each study. When SFC was

used as the primary grain source, Buttrey et al. (2012) reported no difference in DMI or ADG as the concentration of WDGS was increased from 0 to 20%. In contrast, Depenbusch et al. (2008) also fed a SFC-based diet and observed reduced ADG and G:F when WDGS was included at 25% of DM compared to a negative control diet with no byproducts. In DRC based diets, Larson et al. (1993) described a linear relationship as total byproduct inclusion (including wet distillers grains and thin stillage) increased up to 40% of DM, where ADG, G:F, and HCW increased and DMI decreased, which also agrees with Ham et al. (1994) and Al-Suwaiegh et al. (2002). Later, a meta-analysis completed by Klopfenstein (2008) similarly discussed that increasing the concentration of WDGS in the diet resulted in a quadratic effect on performance where performance improved as the inclusion increased from 0 to 40% of DM, but decreased when diets exceeded 50% or greater of dietary DM as WDGS. Similar inconsistencies have been observed for carcass characteristics when feeding WDGS. When replacing WDGS with DRC, Larson et al. (1993) observed no improvement in carcass characteristics except for a tendency for increased HCW. This also agrees with Buttrey et al. (2012) who reported no difference in carcass characteristics when replacing SFC with WDGS. However, Depenbusch et al. (2008) observed lower HCW, dressing percentage, and longissimus dorsi (LM) area when WDGS was included in the diet in place of SFC, but all other carcass variables were not different. Work completed by Al-Suwaiegh et al. (2002) reported that feeding 15% WDGS compared to a control diet with no distillers grain resulted in greater HCW, 12^{th} rib fat thickness, and a tendency for greater yield grade; although it cannot be determined if the positive effects on carcass characteristics should

be contributed to the corn silage or WDGS because different roughages were used in the diet as a part of the experimental design. Overall, this information suggests WDGS are a positive addition to finishing diets when compared to diets that contain no byproducts when fed at the optimal range of 15 to 20% of the dietary DM (Klopfenstein et al., 2008; Corrigan et al., 2009; Quinn et al., 2011) Furthermore, because WDGS provides a cheaper alternative to processed corn, replacing a portion of the grain in the diet may still improve the cost of gain when performance is similar or lower than the grains it is designed to replace.

Combination of WCGF and WDGS

The goal of feeding WCGF and WDGS in combination is to create an associative effect between the positive nutritional qualities of WCGF and WDGS. This concept was initially explored by Loza et al. (2009) in 3 different studies feeding diets including a mixture of DRC and HMC. Experiment 1 evaluated a possible associative effect between WCGF and WDGS. In addition to dietary treatments containing no byproducts, WDGS, or WCGF, two combination diets included a 30 and 60% byproduct blend with both byproducts formulated at 1:1 ratio. However, DMI, ADG and HCW for the 30% blend did not differ from the single byproduct diets and G:F was greater than the 30% WCGF diet but lower than 30% WDGS. The 60% blend resulted in DMI and ADG values similar to the negative control and G:F did not differ with the 30% blend. Hot carcass weight and yield grade was comparable to the control diet without byproducts. In conclusion, an

associative effect was not observed and the blended diets did not outperform the WDGS or WCGF diets.

Experiment 2 investigated the interaction between the inclusion level of various blends of 1:1 WCGF and WDGS (0, 25, 50, or 75% of diet DM) and roughage concentration in the diet. No interactions were observed between roughage level (0 to 7.5% alfalfa) and byproduct blends. However, a quadratic response was observed where cattle consuming the 25 and 50% byproduct blend had the greatest DMI, ADG, and G:F and the 75% blend had the lowest performance, which was similar to the control diet. For carcass characteristics the 25 and 50% blend diet also had the greatest HCW, yield grade, and 12th-rib fat thickness and the 75% diet was comparable to the control diet. A linear effect was also reported for marbling scores, which decreased as byproduct concentration increased in the diet. When combined with the results from the first study, this suggests that the maximum concentration of a 1:1 byproduct blend is between 50 and 60% of the total diet.

Experiment 3 questioned the WDGS inclusion rate (ranging from 0 to 30%), to use in a diet that is formulated with 30% WCGF, which was validated by experiment 1 as the highest performing diet. A quadratic response for increased ADG, HCW, and 12th-rib fat thickness indicated that 15 or 20% of DM was the optimal inclusion of WDGS in a 30% WCGF diet. All other variables for the experiment were not different. Bremer et al. (2009) adjusted this design to determine the optimal inclusion rate of WDGS (ranging from 0 to 40%) when added to a 35% WCGF diet. However, with the increased fixed value of WCGF, all variables were either similar to the control diet (35% WCGF only) or

decreased when WDGS was increased. Therefore, the existing literature suggests that 30% WCGF may be the optimum inclusion level for formulating diets that also include WDGS.

Rumen Function and Health

Functionality of the rumen is crucial for optimal performance of a ruminant animal. Feeding processed corn to finishing cattle has been the most common management strategy to provide an energy dense diet for the highest rate of gain (Samuelson et al., 2016). However, maximum efficiency is achieved when an increased amount of available substrate is fermented over a longer period of time (Owens et al., 1998). Fermentation is facilitated by ruminal microorganisms attaching to feed particles and degrading macromolecules, such as polypeptides and polysaccharides into smaller or individual units that are easily consumed and digested by protozoa and bacteria (Hungate, 1966). Different combinations of feed ingredients will promote growth of individual species of microorganisms and will result in varying metabolic waste products which include VFA, lactic acid, ammonia, hydrogen, carbon dioxide, and methane. Acetate is the predominant VFA produced from the microbial metabolism of substrates such as cellulose, hemicellulose, and starch whereas propionate is the second greatest produced VFA (Murphy et al., 1982). However, acetate:propionate ratio is decreased when high concentrate diets are fed compared to high roughage diets (Christophersen et al., 2008). The acetate:propionate ratio is important because not only does propionate yield more energy than acetate when converted to glucose to support gluconeogenesis (Sharp et al.,

1982), but decreased acetate:propionate is an indicator of reduced methane production because more carbon molecules are used for VFA production and less hydrogen will be bound as methane which will inevitably decrease ruminal pH (Lana et al., 1998). These VFA are either metabolized by other microbial species or directly absorbed through the rumen epithelial wall to be used as a source of energy by the animal. However, absorptive capabilities are dependent on overall ruminal health as ruminal papillae are the main source of nutrient absorption (Penner et al., 2011) and can be negatively impacted by metabolic disorders such as ruminal acidosis.

Ruminal Acidosis

Digestive upset caused by ruminal acidosis occurs from a series of feeding events and/or behaviors over a short or prolonged period of time. Rapid fermentation often leads to acidosis, which may be caused by excessive or erratic consumption of concentrate diets. The most common time for cattle to experience variation in DMI is during transition from a lower energy, high roughage receiving diet to a traditional finishing diet containing high concentrations of readily fermentable energy (Krehbiel et al., 1995). Acidosis may also be caused by delayed feeding time (Erickson et al., 2003), extensive grain processing resulting in more available starch for digestion (Zinn, 1990), or engorgement of feed during the conversion from physical satiation to chemical satiation during the transition period (Forbes, 1986). Microbial fermentation end-products such as organic acids and VFA's will alter the rumen environment and are reflected immediately as fluctuations of ruminal pH in response to feeding behavior (Allen, 1997). Ruminal pH

is highest around feeding time and lowest approximately 12 h after feeding and begins to rise once carbohydrates are consumed by microbes and byproducts of fermentation are removed (Hungate, 1966; Adams and Kartcher, 1984, Tomzcak et al., 2019). Cellulolytic bacteria use available starch and will outcompete fibrolytic bacteria for nutrients, thus resulting in a decrease in the population of fibrolytic bacteria species which negatively impacts fiber digestion and increases organic and lactic acid production as a waste product of the thriving cellulolytic bacteria when there is an excess of starch. Lactic acid utilizing bacteria eventually become engorged because there is too much substrate to manage lactic acid levels. Increased lactic acid decreases the pH of the rumen environment (Kezar and Church, 1979). This low pH is not conducive for maintenance of lactic acid utilizing bacteria populations, and the decline in these species causes even higher accumulation of lactic acid and further decreases rumen pH (Owens et al., 1998). Fibrolytic bacteria species such as *Fibrobacter succinogenes* and *Ruminococcus flavefaciens* become inactive once pH declines below 6.0 (Kezar and Church, 1979) and non-fibrolytic bacteria such as *Lactobacillus vitulimus* and *Megasphaera elsdenii* become inactive at a pH of 4.75 (Russel and Dombrowski, 1980).

Subacute ruminal acidosis is classified as a ruminal pH less than 5.6 and acute acidosis is defined as pH below 5.2 (Cooper and Klopfenstein, 1996). The severity of acidosis depends on the extent of time the rumen environment remains below a pH of 5.6, but is also influenced by the individual tolerance of the animal to decreases in ruminal pH (Bevans et al., 2005). Furthermore, the thresholds used to identify acidosis may need to be reconsidered as we gain improved understanding of the animal response to

fluctuations in ruminal pH by using more advanced detection technology such as pH boluses and learn more about relationships between acidosis and lipopolysaccharide from gram negative bacteria that are associated with ruminal acidosis (Gozho et al., 2005). Increased exposure to acidotic conditions diminishes the integrity and functionality of the rumen epithelial wall (Nagaraja, 2018). Acidosis will promote sloughing of the ruminal epithelium (Ismail et al., 2010) and decrease absorptive capabilities (Owens et al 1998; Minuti et al., 2014) and rumination as a result of ruminal stasis from low pH (Bruce and Huber, 1973). Ultimately this condition results in negative consequences to the animal by limiting the amount of usable nutrients, decreasing performance and DMI, and causing general feelings of malaise.

Ruminal Buffering Capacity and Saliva Production

Individual feed ingredients have the capability to contibute to ruminal alkalinity, with grains having the least buffering capacity, low protein grass forages being intermediate, and legumes and high protein feeds having the greatest buffering capacity (Jasaitis et al., 1987). Giger-Reverdin et al. (2002) concluded that buffering capacity is greater for corn gluten feed in comparison to distillers grains, which is still greater than the buffering capacity of processed corn. The initial pH of byproducts are typically lower than other grains which could be from the fermentation process of manufacturing, and in some cases, the ensiling processes needed to preserve byproducts such as bags or silos and tended to provide a larger potential buffering capacity compared to other feed ingredients that had higher initial pH.

However, the buffering effect from feeds are not as signifiant as the buffering capacity of saliva, where the maximal buffering capacity is observed at pH levels under 5 (Wohlt et al., 1987). Saliva (pH = 8.2 to 8.5) is produced in large quatities by the parotid salivary gland (and other smaller glands including the subamaxilary and sublingual salivary glands) and is comprised of approximatly 120 mmol/L of bicarbonate (HCO_3^-; $pK_a = 3.80$) and ~ 30 mmol/L of hydrogen phosphate (HPO_4^{-2}; $pK_a = 7.21$) ions which contributes to ruminal buffering and alkalinity (Bailey and Balch, 1961). Rather than controlling acid production (which is needed for other ruminal ecology functions), saliva can serve as an additional hydrogen sink. As summarized by Allen (1997), hydrogen ions are removed from the ruminal environment two-fold; 1) the carbonate system in which HCO_3^- binds H^+ to form water and CO_2 and is then removed, and 2) the phosphate system when H^+ are bound to hydrogen phosphate to create dihydrogen phosphate and exit through the omasum. When a rumen has a neutral pH, saliva has a buffering capacity of 50% where-as a slightly more acidic environment of 5.5 increases the buffering capacity to nearly 100%. Greater salivary secretions are stimulated by the parasympathetic nervous system during feeding events (Kay, 1960) and by greater DMI and rumination (McDougall, 1948; Carter and Grovum, 1990; Allen, 1997).

Rumination

Rumination is the physical act of a ruminant animal regurgitating a feed bolus from the reticulum to the mouth to be re-masticated to mix digesta with saliva and decrease the particle size of the feed. However, preceeding events, as described by Ash

and Kay (1959), are needed for successful rumination. Ruminal pillars contract to mix ruminal contents and move digesta to exit the rumen or to be ruminated. When the reticulo-omasal orifice is distended, one contraction of the reticulum delivers the feed bolus to the oral cavity with a simultaneous increase in saliva flow. In addition, salivary flow may increase for 30 to 60 s before rumination. Ruminating can be increased by greater roughage size and quantity as described by Jennings et al. (2020) when using corn stalks as a roughage source. In addition, lower inclusion of a larger particle size could replace a greater inclusion of smaller particle size (Gentry et al., 2016). Furthermore, increasing roughage particle size will increase digestibility of the roughage because smaller feed particles spend less time in the rumen and are not ruminated because they do not need to be reduced to flow out of the rumen (Udén, 1988). Quality of the roughage source also effects time spent ruminating (Welch and Smith, 1970; Shain et al., 1999; Benton et al., 2015). Shain et al. (1999) added another level to their factorial arrangement and compared varying particle sizes of roughage (2.54 and 12.7 cm) and two roughage sources including wheat straw and alfalfa hay. The conclusion reached by Shain et al. (1999) was that cattle consuming the roughage source with the greatest “roughage factor” (wheat straw) spent more time ruminating and also that the wheat straw ground at a larger particle size resulted in more rumination compared to the smaller wheat straw particle size. However, the smaller wheat straw particle size stimulated more rumination than the larger sized alfalfa hay. When decreased particle size resulted in less time spent ruminating, ruminal pH was lower. This also agrees with the results described by Woodford and Murphy (1988). Although there are positives associated with including

roughage in a high energy diet, there is a balance between too much and too little fiber inclusion. Too much fiber will decrease animal performance because of energy dilution from the original formulation and insufficient levels of fiber may decrease performance of cattle from increased acid load from rapid microbial fermentation (Hales et al., 2014; Jennings et al., 2020).

Increasing Fiber and Physically Effective NDF

Mitigation of low ruminal pH can be achieved by increasing overall NDF concentration of the diet (Owens, 1998), yet increasing NDF may also decrease overall DMI because of physical limitations such a gut fill and slower passage rate. In contrast, Defoor et al. (2002) observed a positive correlation between increased NEg intake/kg of $BW^{0.75}$ and NDF concentration of various roughage sources including cottonseed hulls, alfalfa, and sudan silage. The greater DMI was speculated to be from reduced negative post-ingestive feedback from digestive upset or compensation for a lower energy diet. Although there may be an increase in DMI, the lower energy diet does not translate to greater retained energy (Hales et al., 2014). Therefore, increasing the composition of physically effective NDF (peNDF) may be a better solution to target increased rumination and saliva production to buffer ruminal pH (Allen, 1997). Physically effective NDF is the combined measurement of NDF concentration and particle size of an individual ingredient or diet that influences rumination and ruminal contractions. Because this method of characterizing fiber measures both the physical and chemical properties that contribute to rumination, it is considered to be a more uniform and descriptive

measurement of fiber than traditional nutrient concentrations such as NDF (Mertens, 1997). To determine the appropriate particle size which will exit the rumen without additional rumination, Cardoza (1985) washed manure samples through screens and observed 5% of particles were retained on a screen measuring 3.35 mm with a larger majority captured on screens varying from 0.40 to 1.20 mm. These results led Cardoza (1985) to conclude that particle sizes of 1.20 mm or less do not contribute to rumination stimulation and exit the rumen with ease, whereas particles that were larger than 3.35 mm would contribute to rumination. A standardized method to characterize the particle size distribution of diets and ingredients was first described by Lammers et al. (1996) to develop an on-site particle separator that mimicked the laboratory-scale ASAE standard S424. These plans would later transition to the current 5-tier Penn State Particle Separator (PSPS) with simplified pore diameters that included 19.0, 8.0, 4.0, 1.18 mm pores and one solid bottom tier. As mentioned previously, peNDF may be an important predictor of rumination and ruminal buffering capacity and has only recently been evaluated in beef feedlot diets (Gentry et al., 2016; Weiss et al., 2017; Jennings et al 2020) where research suggests that increasing the roughage particle size in low forage diets, such as those provided to feedlot cattle, may provide a greater buffering capacity and/or allow for a reduction in the concentration of dietary roughage. Gentry et al. (2016) reported that the peNDF of WCGF was intermediate between SFC and corn stalks. However, additional research needs to be completed to quantify the peNDF of non-forage fibrous feedstuffs such as WDGS and WCGF and determine how this may impact rumen buffering and animal performance.

Effects of Byproducts on Ruminal Health and Digestion

Mechanically processed corn is an ideal feed source for cattle because of the concentrated starch within the endosperm of the grain. An important consideration in feedlot diets is minimizing the cost per unit of energy fed, which favors the use of high concentrate diets (Brown et al., 2006). In addition to the high energy value of SFC (NEg = 1.67 Mcal/kg; NASEM, 2016), fermentation of available starch in processed grains is very rapid. For example, SFC is a commonly used feed ingredient in feedlots located in the southern plains and contains high concentrations of readily degradable starch due to the gelatinization of the starch molecules present within the endosperm (Zinn et al., 2002). Diets with greater energy availability cause a steeper decrease in ruminal pH and will return to pre-challenge pH over an increased period of time (Krehbiel et al., 1995; Bevans et al., 2005).

Corn-milling byproducts are composed of un-lignified fibrous structures that are fermented at a slower rate (Galyean and Hubbert, 2014) which will slow the accumulation of endproducts of microbial fermentation (Owens et al., 1998). Firkins et al. (1985) compared the effects of including WCGF and DCGF in the diet on rumen fermentation characteristics and concluded that diets with WCGF had improved pH in comparision to DCGF. They attributed this effect to the larger particle size of WCGF, which may have caused greater rumination and salivation. Gentry et al. (2016) reported the particle size of WCGF when shaken using the PSPS and 68.60% of the particles were > 4.0 mm in diameter, which supports the conclusion made by Firkins et al. (1985). In addition, Montgomery et al. (2004) observed greater passage rate (which particle size

could also attribute to this) when 38% WCGF was included in the diet in comparision to a SFC diet with no byproduct. However, despite greater passage rate, total tract digestibility of OM and NDF was improved with the addition of WCGF. There is no data to report for the particle size of DCGF. In addition, feeding 40% WDGS numerically decreased ruminal pH in comparison to a diet that did not have byproduct (Corrigan et al., 2009). Felix and Loerch, (2011) speculated that the lower pH caused from feeding distillers grains could be caused from H_2SO_4 production from the available S from distillers grains and increased H^+ ion concentration at a low pH. As processed corn is replaced by WCGF, total organic acid production is decreased which translates to a greater minimum ruminal pH and will return to baseline ruminal pH faster than when feeding a diet that is composed of higher starch (Krehbiel et al., 1995).

When pH is altered by the inclusion of byproducts in the diet, this will positively or negativly effect microorganism populations which could in turn impact nutrient digestibility. Buttrey et al. (2012) observed a tendency for greater manure DM and numerically increased manure OM when cattle were fed 20% WDGS in comparison to a control diet without WDGS. These results are consistent with the linear decrease in digestibility reported by Luebbe et al. (2012) when feeding WDGS in increasing increments ranging from 0 to 60% in SFC diets. The lower digestibility reported in these studies may be a result of the small particle size of WDGS, because a faster passage rate for the diets containing WDGS would likely negatively impact digestibility of nutrients. In contrast, Hales et al. (2012) observed greater NDF digestibility when diets included WDGS at 30% in comparison to a negative control diet that did not contain WDGS. This

suggests that perhaps pH of the rumen of cattle consuming WDGS is adequate to support the function of fibrolytic species of bacteria. However, the higher manure N excretion observed by Hales et al. (2012) is consistent with that reported by Buttrey et al. (2012) and Luebbe et al. (2012) and suggests that the greater crude protein provided by WDGS was not needed to meet the animals' overall protein requirements.

CONCLUSIONS FROM THE LITERATURE

Feeding corn-milling byproducts to cattle is a popular management strategy to reduce the cost of beef diets. Furthermore, using these feedstuffs in place of more expensive processed grains has positively influenced both cattle performance and cost of gain, although some results have been inconsistent and are likely influenced by differences in concentrations of other ingredients in the diet. Fibrous corn-milling byproducts may also provide a route to mitigate fluctuations in ruminal pH and decrease the incidence of ruminal acidosis. Cattle use biological systems to regulate ruminal pH such as the buffering capacity of saliva and rumination. Therefore, strategically incorporating fibrous, corn-milling byproducts into the diet may maximize these functions and result in improved rumen health.

LITERATURE CITED

Adams, D. C., and R. J. Kartchner. 1984. Effect of level of forage intake on rumen ammonia, pH, liquid volume and liquid dilution rate in beef cattle. J. Anim. Sci. 58(3):708-713. doi: 10.2527/jas1984.583708x

Allen, M. S. 1997. Relationship between fermentation acid production in the rumen and the requirement for physically effective fiber. J. Dairy Sci. 80(7):1447-1462. doi: 10.3168/jds.s0022-0302(97)76074-0

Al-Suwaiegh, S., K. Fanning, R. Grant, C. Milton, and T. J. Klopfenstein. 2002. Utilization of distillers grains from the fermentation of sorghum or corn in diets for finishing beef and lactating dairy cattle. J. Anim. Sci. 80(4):1105-1111. doi: 10.2527/2002.8041105x

Ash, R., and R. Kay. 1959. Stimulation and inhibition of reticulum contractions, rumination and parotid secretion from the forestomach of conscious sheep. J. Physiol. 149(1):43. doi: 10.1113/jphysiol.1959.sp006324

Association of American Feed Control Officials. 1996. Official publication, Atlanta, GA.

Bailey, C. B., and C. C. Balch. 1961. Saliva secretion and its relation to feeding in cattle: 1. The composition and rate of secretion of parotid saliva in a small steer. Br. J. Nutr. 15(3):371-382. doi: 10.1079/BJN19610047

Benton, J. R., A. K. Watson, G. E. Erickson, T. J. Klopfenstein, K. J. V. Pol, N. F. Meyer, and M. A. Greenquist. 2015. Effects of roughage source and inclusion in beef finishing diets containing corn wet distillers' grains plus solubles. J. Anim. Sci. 93(9):4358-4367. doi: 10.2527/jas.2015-9211

Bevans, D. W., K. A. Beauchemin, K. S. Schwartzkopf-Genswein, J. J. McKinnon, and T. A. McAllister. 2005. Effect of rapid or gradual grain adaptation on subacute acidosis and feed intake by feedlot cattle. J. Anim. Sci. 83(5):1116-1132. doi: 10.2527/2005.8351116x

Blasi, D. A., M. Brouk, J. Drouillard, and S. Montgomery. 2001. Corn gluten feed, composition and feeding value for beef and dairy cattle. In: No. MF2488. Kansas State University, Manhattan. p. 1-15.

Block, H. C., C. N. Macken, T. J. Klopfenstein, G. E. Erickson, and R. A. Stock. 2005. Optimal wet corn gluten and protein levels in steam-flaked corn-based finishing diets for steer calves. J. Anim. Sci. 83(12):2798-2805. doi: 10.2527/2005.83122798x

Bremer, V. R., J. R. Benton, M. K. Luebbe, K. J. Hanford, G. E. Erickson, T. J. Klopfenstein, and R. Stock. 2009. Wet distillers grains plus solubles or solubles in feedlot diets containing wet corn gluten feed. In: 2009 Nebraska Beef Cattle Reports. Rep. No. 506. Univ. Nebraska, Lincoln. p. 64-65.

Brown, M. S., C. H. Ponce, and R. Pulikanti. 2006. Adaptation of beef cattle to high-concentrate diets: Performance and ruminal metabolism. J. Anim. Sci. 84(suppl_13):E25-E33. doi: 10.2527/2006.8413_supplE25x

Bruce, L. A., and T. L. Huber. 1973. Inhibitory effect of acid in the intestine on rumen motility in sheep. J. Anim. Sci. 37(1):164-168. doi: 10.2527/jas1973.371164x

Buttrey, E. K., N. A. Cole, K. H. Jenkins, B. E. Meyer, F. T. McCollum, III, S. L. M. Preece, B. W. Auvermann, K. R. Heflin, and J. C. MacDonald. 2012. Effects of twenty percent corn wet distillers grains plus solubles in steam-flaked and dry-rolled corn-based finishing diets on heifer performance, carcass characteristics, and manure characteristics. J. Anim. Sci. 90(13):5086-5098. doi: 10.2527/jas.2012-5198

Cardoza, R. 1985. Threshold size and factors affecting fecal particle weight distribution. Masters. Univ. of Georgia, Athens.

Carter, R. R., and W. L. Grovum. 1990. A review of the physiological significance of hypertonic body fluids on feed intake and ruminal function: salivation, motility and microbes. J. Anim. Sci. 68(9):2811-2832. doi: 10.2527/1990.6892811x

Chang, I.-S., B.-H. Kim, P.-K. Shin, and W.-K. Lee. 1995. Bacterial contamination and its effects on ethanol fermentation. J. Microbiol. Biotechnol. 5(6):309-314.

Christophersen, C. T., A.-D. G. Wright, and P. E. Vercoe. 2008. In vitro methane emission and acetate:propionate ratio are decreased when artificial stimulation of the rumen wall is combined with increasing grain diets in sheep. J. Anim. Sci. 86(2):384-389. doi: 10.2527/jas.2007-0373

Connolly, C. 1999. Bacterial contaminants and their effects on alcohol production. In: K. A. Jacques, T. P. Lyons and D. R. Kelsall, editors, The alcohol textbook 3. Nottingham University Press, Nottingham, U.K. p. 317-334.

Cooper, R., and T. Klopfenstein. 1996. Effects of rumensin and feed intake variation on ruminal ph: Update on rumensin/tylan/micotyl for the professional feedlot

consultant. In: 1996 Nebraska Beef Cattle Report. Rep. No. 430. Univ. of Nebraska, Lincoln. p. 49-52.

Corn Refiners Association. Inc. 1989. Corn wet-milled feed products. 3rd ed, Washington, DC.

Corrigan, M. E., G. E. Erickson, T. J. Klopfenstein, M. K. Luebbe, K. J. Vander Pol, N. F. Meyer, C. D. Buckner, S. J. Vanness, and K. J. Hanford. 2009. Effect of corn processing method and corn wet distillers grains plus solubles inclusion level in finishing steers. J. Anim. Sci. 87(10):3351-3362. doi: 10.2527/jas.2009-1836

Defoor, P. J., M. L. Galyean, G. B. Salyer, G. A. Nunnery, and C. H. Parsons. 2002. Effects of roughage source and concentration on intake and performance by finishing heifers. J. Anim. Sci. 80(6):1395-1404. doi: 10.2527/2002.8061395x

Depenbusch, B. E., J. S. Drouillard, E. R. Loe, J. J. Higgins, M. E. Corrigan, and M. J. Quinn. 2008. Efficacy of monensin and tylosin in finishing diets based on steam-flaked corn with and without corn wet distillers grains with solubles. J. Anim. Sci. 86(9):2270-2276. doi: 10.2527/jas.2007-0017

Dien, B. S., R. J. Bothast, N. N. Nichols, and M. A. Cotta. 2002. The US corn ethanol industry: an overview of current technology and future prospects. Int. Sugar J. 104(1241):204-211.

Domby, E. M., U. Y. Anele, K. K. Gautam, J. E. Hergenreder, A. R. Pepper-Yowell, and M. L. Galyean. 2014. Interactive effects of bulk density of steam-flaked corn and concentration of Sweet Bran on feedlot cattle performance, carcass characteristics, and apparent total tract nutrient digestibility. J. Anim. Sci. 92(3):1133-1143. doi: 10.2527/jas.2013-7038

Drewnoski, M., D. Pogge, and S. Hansen. 2014. High-sulfur in beef cattle diets: a review. J. Anim. Sci. 92(9):3763-3780. doi: 10.2527/jas.2013-7242

Ellis, G. 1959. The maillard reaction. In: M. L. Wolfrom, editor, Adv. Carbohydr. Chem. No. 14. p. 63-134.

Erickson, G. E., C. T. Milton, K. C. Fanning, R. J. Cooper, R. S. Swingle, J. C. Parrott, G. Vogel, and T. J. Klopfenstein. 2003. Interaction between bunk management and monensin concentration on finishing performance, feeding behavior, and ruminal metabolism during an acidosis challenge with feedlot cattle. J. Anim. Sci. 81(11):2869-2879. doi: 10.2527/2003.81112869x

Felix, T. L., and S. C. Loerch. 2011. Effects of haylage and monensin supplementation on performance, carcass characteristics, and ruminal metabolism of feedlot cattle fed diets containing 60% dried distillers grains. J. Anim. Sci. 89(8):2614-2623. doi: 10.2527/jas.2010-3716

Firkins, J. L., L. L. Berger, and G. C. Fahey, Jr. 1985. Evaluation of wet and dry distillers grains and wet and dry corn gluten feeds for ruminants. J. Anim. Sci. 60(3):847-860. doi: 10.2527/jas1985.603847x

Forbes, J. M. 1986. The voluntary food intake of farm animals. Butterworth-Heinemann.

Galyean, M., and M. Hubbert. 2014. Traditional and alternative sources of fiber—Roughage values, effectiveness, and levels in starting and finishing diets. Prof. Anim. Sci. 30(6):571-584. doi: 10.15232/pas.2014-01329

Gentry, W. W., C. P. Weiss, C. M. Meredith, F. T. McCollum, N. A. Cole, and J. S. Jennings. 2016. Effects of roughage inclusion and particle size on performance and rumination behavior of finishing beef steers. J. Anim. Sci. 94(11):4759-4770. doi: 10.2527/jas.2016-0734

Giger-Reverdin, S., C. Duvaux-Ponter, D. Sauvant, O. Martin, I. N. do Prado, and R. Müller. 2002. Intrinsic buffering capacity of feedstuffs. Anim. Feed Sci. Technol. 96(1-2):83-102. doi: 10.1016/s0377-8401(01)00330-3

Gould, D. H. 1998. Polioencephalomalacia. J. Anim. Sci. 76(1):309-314. doi: 10.2527/1998.761309x

Gozho, G., J. Plaizier, D. Krause, A. Kennedy, and K. Wittenberg. 2005. Subacute ruminal acidosis induces ruminal lipopolysaccharide endotoxin release and triggers an inflammatory response. J. Dairy Sci. 88(4):1399-1403

Hales, K. E., T. M. Brown-Brandl, and H. C. Freetly. 2014. Effects of decreased dietary roughage concentration on energy metabolism and nutrient balance in finishing beef cattle. J. Anim. Sci. 92(1):264-271. doi: 10.2527/jas.2013-6994

Hales, K. E., N. A. Cole, and J. C. MacDonald. 2012. Effects of corn processing method and dietary inclusion of wet distillers grains with solubles on energy metabolism, carbon–nitrogen balance, and methane emissions of cattle. J. Anim. Sci. 90(9):3174-3185. doi: 10.2527/jas.2011-4441

Ham, G. A., R. A. Stock, T. J. Klopfenstein, and R. P. Huffman. 1995. Determining the net energy value of wet and dry corn gluten feed in beef growing and finishing diets. J. Anim. Sci. 73(2):353-359. doi: 10.2527/1995.732353x

Ham, G. A., R. A. Stock, T. J. Klopfenstein, E. M. Larson, D. H. Shain, and R. P. Huffman. 1994. Wet corn distillers byproducts compared with dried corn distillers grains with solubles as a source of protein and energy for ruminants. J. Anim. Sci. 72(12):3246-3257. doi: 10.2527/1994.72123246x

Hungate, R. E. 1966. The rumen and its microbes. Elsevier.

Hussein, H. S., and L. L. Berger. 1995. Effects of feed intake and dietary level of wet corn gluten feed on feedlot performance, digestibility of nutrients, and carcass characteristics of growing-finishing beef heifers. J. Anim. Sci. 73(11):3246-3252. doi: 10.2527/1995.73113246x

Iowa Beef Center. 2014. Ethanol coproducts for beef cattle. In: Iowa Beef Center Report. Rep. No. 200B, Iowa State University Extension and Outreach. p 1-6.

Ismail, M., A. Mahmoud, M. Nasr, and Y. Badr. 2010. Clinical and laboratory studies on experimentally induced acute ruminal lactic acidosis in male goats. J. Vet. Sci. 31(1):53-62.

Jasaitis, D., J. Wohlt, and J. Evans. 1987. Influence of feed ion content on buffering capacity of ruminant feedstuffs in vitro. J. Dairy Sci. 70(7):1391-1403. doi: 10.3168/jds.s0022-0302(87)80161-3

Jennings, J., C. Lockard, L. Tedeschi, and T. Lawrence. 2020. Effects of corn stalk inclusion rate on rumination and ruminal pH in finishing beef steers. Appl. Anim. Sci. 36(3):377-388. doi: 10.15232/aas.2019-01947

Kay, R. N. 1960. The rate of flow and composition of various salivary secretions in sheep and calves. J. Physiol. 150(3):515. doi: 10.1113/jphysiol.1960.sp006402

Kezar, W. W., and D. C. Church. 1979. Ruminal changes during the onset and recovery of induced lactic acidosis in sheep. J. Anim. Sci. 49(5):1161-1167. doi: 10.2527/jas1979.4951161x

Klopfenstein, T. 1996. Distillers grains as an energy source and effect of drying on protein availability. Anim. Feed Sci. Technol. 60(3-4):201-207. doi: 10.1016/0377-8401(96)00978-9

Klopfenstein, T. J., G. E. Erickson, and V. R. Bremer. 2008. BOARD-INVITED REVIEW: Use of distillers by-products in the beef cattle feeding industry. J. Anim. Sci. 86(5):1223-1231. doi: 10.2527/jas.2007-0550

Koger, T., D. Wulf, A. Weaver, C. Wright, K. Tjardes, K. Mateo, T. Engle, R. Maddock, and A. Smart. 2010. Influence of feeding various quantities of wet and dry distillers grains to finishing steers on carcass characteristics, meat quality, retail-case life of ground beef, and fatty acid profile of longissimus muscle. J. Anim. Sci. 88(10):3399-3408. doi: 10.2527/jas.2009-2708

Krehbiel, C. R., R. A. Stock, D. W. Herold, D. H. Shain, G. A. Ham, and J. E. Carulla. 1995. Feeding wet corn gluten feed to reduce subacute acidosis in cattle. J. Anim. Sci. 73(10):2931-2939. doi: 10.2527/1995.73102931x

Lammers, B., D. Buckmaster, and A. J. Heinrichs. 1996. A simple method for the analysis of particle sizes of forage and total mixed rations. J. Dairy Sci. 79(5):922-928. doi: 10.3168/jds.s0022-0302(96)76442-1

Lana, R. P., J. B. Russell, and M. E. Van Amburgh. 1998. The role of pH in regulating ruminal methane and ammonia production. J. Anim. Sci. 76(8):2190-2196. doi: 10.2527/1998.7682190x

Larson, E., R. Stock, T. Klopfenstein, M. Sindt, and R. Huffman. 1993. Feeding value of wet distillers byproducts for finishing ruminants. J. Anim. Sci. 71(8):2228-2236. doi: 10.2527/1993.7182228x

Leibovich, J., J. Vasconcelos, and M. Galyean. 2009. Effects of corn processing method in diets containing sorghum wet distillers grain plus solubles on performance and carcass characteristics of finishing beef cattle and on in vitro fermentation of diets. J. Anim. Sci. 87(6):2124-2132. doi: 10.2527/jas.2009-87-9-3065

Lodge, S. L., R. A. Stock, T. J. Klopfenstein, D. H. Shain, and D. W. Herold. 1997. Evaluation of corn and sorghum distillers byproducts. J. Anim. Sci. 75(1):37-43. doi: 10.2527/1997.75137x

Loza, P. L., C. D. Buckner, K. J. Vander Pol, G. E. Erickson, T. J. Klopfenstein, and R. A. Stock. 2010. Effect of feeding combinations of wet distillers grains and wet corn gluten feed to feedlot cattle. J. Anim. Sci. 88(3):1061-1072. doi: 10.2527/jas.2009-2190

Luebbe, M. K., J. M. Patterson, K. H. Jenkins, E. K. Buttrey, T. C. Davis, B. E. Clark, F. T. McCollum, III, N. A. Cole, and J. C. MacDonald. 2012. Wet distillers grains plus solubles concentration in steam-flaked-corn-based diets: Effects on feedlot cattle performance, carcass characteristics, nutrient digestibility, and ruminal fermentation characteristics1. J. Anim. Sci. 90(5):1589-1602. doi: 10.2527/jas.2011-4567

Lushia, W., and P. Heist. 2005. Antibiotic resistant bacteria in fuel ethanol fermentations. In: Ethanol producer magazine, May 2005 Issue.

Macken, C. N., G. E. Erickson, T. J. Klopfenstein, and R. A. Stock. 2004. Effects of concentration and composition of wet corn gluten feed in steam-flaked corn-based finishing diets. J. Anim. Sci. 82(9):2718-2723. doi: 10.2527/2004.8292718x

Makanjuola, D., A. Tymon, and D. Springham. 1992. Some effects of lactic acid bacteria on laboratory-scale yeast fermentations. Enzyme Microb. Technol. 14(5):350-357. doi: 10.1016/0141-0229(92)90002-6

May, M. L., M. J. Quinn, N. DiLorenzo, D. R. Smith, and M. L. Galyean. 2011. Effects of roughage concentration in steam-flaked corn-based diets containing wet

distillers grains with solubles on feedlot cattle performance, carcass characteristics, and in vitro fermentation. J. Anim. Sci. 89(2):549-559. doi: 10.2527/jas.2010-3049

McDougall, E. 1948. Studies on ruminant saliva. 1. The composition and output of sheep's saliva. Biochem. J. 43(1):99. doi: 10.1042/bj0430099

Mertens, D. 1997. Creating a system for meeting the fiber requirements of dairy cows. J. Dairy Sci. 80(7):1463-1481. doi: 10.3168/jds.s0022-0302(97)76075-2

Minuti, A., S. Ahmed, E. Trevisi, F. Piccioli-Cappelli, G. Bertoni, N. Jahan, and P. Bani. 2014. Experimental acute rumen acidosis in sheep: Consequences on clinical, rumen, and gastrointestinal permeability conditions and blood chemistry. J. Anim. Sci. 92(9):3966-3977. doi: 10.2527/jas.2014-7594

Montgomery, S. P., J. S. Drouillard, E. C. Titgemeyer, J. J. Sindt, T. B. Farran, J. N. Pike, C. M. Coetzer, A. M. Trater, and J. J. Higgins. 2004. Effects of wet corn gluten feed and intake level on diet digestibility and ruminal passage rate in steers. J. Anim. Sci. 82(12):3526-3536. doi: 10.2527/2004.82123526x

Morine, S. J., M. E. Drewnoski, and S. L. Hansen. 2014. Increasing dietary neutral detergent fiber concentration decreases ruminal hydrogen sulfide concentrations in steers fed high-sulfur diets based on ethanol coproducts. J. Anim. Sci. 92(7):3035-3041. doi: 10.2527/jas.2013-7339

Murphy, M. R., R. L. Baldwin, and L. J. Koong. 1982. Estimation of stoichiometric parameters for rumen fermentation of roughage and concentrate diets. J. Anim. Sci. 55(2):411-421. doi: 10.2527/jas1982.552411x

Nagaraja, T. G. 2018. Ruminal epithelial integrity and liver abscesses in feedlot cattle. J. Anim. Sci. 96(suppl_2):218-219. doi: 10.1093/jas/sky073.404

Nichols, C., V. Bremer, A. Watson, C. Buckner, J. Harding, G. Erickson, T. Klopfenstein, and D. Smith. 2013. The effect of sulfur and use of ruminal available sulfur as a model to predict incidence of polioencephalomalacia in feedlot cattle. Bov. Pract. (Stillwater) 47(1):47-53.

NRC. 2005. Mineral Tolerance of Domestic Animals. Natl. Acad. Press, Washington, DC.

NASEM (National Academics of Science, E., and Medicine.). 2016. Nutrient requirements of beef cattle. 8th rev. ed. Natl. Acad. Press, Washington, DC.

Nuttelman, B. L., W. A. Griffin, J. R. Benton Benton, G. Erickson, and T. Klopfenstein. 2011. Comparing dry, wet, or modified distillers grains plus solubles on feedlot

cattle performance. In: 2011 Nebraska Beef Cattle Report. Rep. No. 619. Univ. Nebraska, Lincoln. p. 50-52.

Orskov, E. 1989. Recent advances in evaluation of roughages as feeds for ruminants. Adv. Anim. Nutr.:102-108.

Owens, F. N., D. S. Secrist, W. J. Hill, and D. R. Gill. 1998. Acidosis in cattle: a review. J. Anim. Sci. 76(1):275-286. doi: 10.2527/1998.761275x

Parsons, C. H., J. T. Vasconcelos, R. S. Swingle, P. J. Defoor, G. A. Nunnery, G. B. Salyer, and M. L. Galyean. 2007. Effects of wet corn gluten feed and roughage levels on performance, carcass characteristics, and feeding behavior of feedlot cattle. J. Anim. Sci. 85(11):3079-3089. doi: 10.2527/jas.2007-0149

Penner, G. B., M. A. Steele, J. R. Aschenbach, and B. W. McBride. 2011. Ruminant nutrition symposium: Molecular adaptation of ruminal epithelia to highly fermentable diets. J. Anim. Sci. 89(4):1108-1119. doi: 10.2527/jas.2010-3378

Quinn, M. J., M. L. May, N. DiLorenzo, C. H. Ponce, D. R. Smith, S. L. Parr, and M. L. Galyean. 2011. Effects of roughage source and distillers grain concentration on beef cattle finishing performance, carcass characteristics, and in vitro fermentation. J. Anim. Sci. 89(8):2631-2642. doi: 10.2527/jas.2010-3563

Russell, J. B., and D. Dombrowski. 1980. Effect of pH on the efficiency of growth by pure cultures of rumen bacteria in continuous culture. Appl. Environ. Microbiol. 39(3):604-610. doi: 10.1128/aem.39.3.604-610.1980

Samuelson, K. L., M. E. Hubbert, M. L. Galyean, and C. A. Löest. 2016. Nutritional recommendations of feedlot consulting nutritionists: The 2015 New Mexico State and Texas Tech University survey. J. Anim. Sci. 94(6):2648-2663. doi: 10.2527/jas.2016-0282

Sarturi, J. O., G. E. Erickson, T. J. Klopfenstein, J. T. Vasconcelos, W. A. Griffin, K. M. Rolfe, J. R. Benton, and V. R. Bremer. 2013. Effect of sulfur content in wet or dry distillers grains fed at several inclusions on cattle growth performance, ruminal parameters, and hydrogen sulfide. J. Anim. Sci. 91(10):4849-4860. doi: 10.2527/jas.2012-5627

Scott, T. L., C. T. Milton, G. E. Erickson, T. J. Klopfenstein, and R. A. Stock. 2003. Corn processing method in finishing diets containing wet corn gluten feed. J. Anim. Sci. 81(12):3182-3190. doi: 10.2527/2003.81123182x

Shain, D. H., R. A. Stock, T. J. Klopfenstein, and D. W. Herold. 1999. The effect of forage source and particle size on finishing yearling steer performance and ruminal metabolism. J. Anim. Sci. 77(5):1082-1092. doi: 10.2527/1999.7751082x

Sharma, V., K. D. Rausch, M. E. Tumbleson, and V. Singh. 2007. Comparison between granular starch hydrolyzing enzyme and conventional enzymes for ethanol production from maize starch with different amylose: amylopectin ratios. Starch-Stärke 59(11):549-556. doi: 10.1002/star.200700631

Sharp, W. M., R. R. Johnson, and F. N. Owens. 1982. Ruminal vfa production with steers fed whole or ground corn grain. J. Anim. Sci. 55(6):1505-1514. doi: 10.2527/jas1982.5561505x

Solomon, B. D., J. R. Barnes, and K. E. Halvorsen. 2007. Grain and cellulosic ethanol: History, economics, and energy policy. Biomass Bioenergy 31(6):416-425. doi: 10.1016/j.biombioe.2007.01.023

Stock, R. A., J. M. Lewis, T. J. Klopfenstein, and C. T. Milton. 2000. Review of new information on the use of wet and dry milling feed by-products in feedlot diets. J. Anim. Sci. 77(suppl_E):1-12. doi: 10.2527/jas2000.77E-Suppl1w

Tomczak, D. J., C. L. Lockard, J. S. Jennings, and J. T. Richeson. 2019. Performance, rumination, and rumen pH responses to different dietary energy density and feed management strategies in auction-derived feedlot cattle. J. Anim. Sci. 97(11):4682-4690. doi: 10.1093/jas/skz323

Udén, P. 1988. The effect of grinding and pelleting hay on digestibility, fermentation rate, digesta passage and rumen and faecal particle size in cows. Anim. Feed Sci. Technol. 19(1):145-157. doi: 10.1016/0377-8401(88)90063-6

Vanness, S., T. J. Klopfenstein, G. E. Erickson, and K. Karges. 2009. Sulfur in distillers grains. In: 2009 Nebraska Beef Cattle Reports. Rep. No. 538. Univ. Nebraska, Lincoln. p. 79-80.

Weiss, C. P., W. W. Gentry, C. M. Meredith, B. E. Meyer, N. A. Cole, L. O. Tedeschi, F. T. McCollum, III, and J. S. Jennings. 2017. Effects of roughage inclusion and particle size on digestion and ruminal fermentation characteristics of beef steers. J. Anim. Sci. 95(4):1707-1714. doi: 10.2527/jas.2016.1330

Welch, J., and A. Smith. 1970. Forage quality and rumination time in cattle. J. Dairy Sci. 53(6):797-800. doi: 10.3168/jds.s0022-0302(70)86293-2

Winkler-Moser, J. K., and L. Breyer. 2011. Composition and oxidative stability of crude oil extracts of corn germ and distillers grains. Ind. Crops. Prod. 33(3):572-578. doi: 10.1016/j.indcrop.2010.12.013

Wohlt, J., D. Jasaitis, and J. Evans. 1987. Use of acid and base titrations to evaluate the buffering capacity of ruminant feedstuffs in vitro. J. Dairy Sci. 70(7):1465-1470. doi: 10.3168/jds.s0022-0302(87)80170-4

Woodford, S., and M. Murphy. 1988. Effect of forage physical form on chewing activity, dry matter intake, and rumen function of dairy cows in early lactation. J. Dairy Sci. 71(3):674-686. doi: 10.3168/jds.s0022-0302(88)79606-x

Zinn, R. A. 1990. Influence of flake density on the comparative feeding value of steam-flaked corn for feedlot cattle. J. Anim. Sci. 68(3):767-775. doi: 10.2527/1990.683767x

Zinn, R. A., F. N. Owens, and R. A. Ware. 2002. Flaking corn: processing mechanics, quality standards, and impacts on energy availability and performance of feedlot cattle. J. Anim. Sci. 80(5):1145-1156. doi: 10.2527/2002.8051145x

Table 1. Tabular nutrient concentrations of wet or dry corn gluten feed compared to steam-flaked corn (DM basis)[1]

Nutrient, %	SFC[2]	WCGF[3]	DCGF[4]
Dry Matter	80.7	43.8	88.9
Crude Protein	8.48	21.7	22.6
Fat	3.19	4.29	3.32
Total Starch	76.2	15.2	16.9
NDF	8.97	38.5	35.1
ADF	3.59	11.8	11.2
TDN	95.0	86.0	80.0
Ash	1.26	6.40	8.20
NEm, Mcal/kg	2.38	2.12	1.94
NEg, Mcal/kg	1.67	1.45	1.30

[1]NASEM, 2016.
[2]Steam-Flaked Corn (SFC).
[3]Wet corn Gluten Feed (WCGF).
[4]Dried Corn Gluten Feed (DCGF).

Table 2. Nutrient concentrations of select corn-dry milling byproducts (DM basis)[1,2]

	DDGS[3]			MDGS[4]		WDGS[5]		
Nutrient, %	Normal[6]	Low Fat	De-Oiled	Normal[6]	Low Fat	Normal[6]	Low Fat	De-Oiled
Dry Matter	90.0	89.7	89.3	47.8	49.3	31.4	38.0	33.0
Crude Protein	30.8	31.4	27.9	29.1	31.6	30.6	32.6	34.7
Starch	5.88	4.72	-	3.36	2.55	6.06	4.77	-
Fat	10.7	7.36	3.57	10.2	7.63	10.8	7.78	2.72
NDF	33.7	26.7	33.8	28.7	26.4	31.5	31.3	34.1
ADF	16.2	12.4	16.9	14.8	13.9	15.3	17.4	14.1
Ash	5.32	4.99	4.64	6.65	6.3	5.13	3.97	2.33
TDN	89.9	90.8	88.2	93.0	94.2	98.0	96.7	93.5
NEm, Mcal/kg	2.21	2.27	2.18	2.33	2.35	2.47	2.42	2.33
NEg, Mcal/kg	1.52	1.63	1.58	1.74	1.69	1.74	1.76	1.69

[1]Values reported are an average of distillers grain samples collected from various Iowa ethanol plants and beef producers unless otherwise noted.

[2]Table adapted from Iowa Beef Center, (2014).

[3]Dried distillers grains with solubles (DDGS).

[4]Modified distillers grains with solubles (MDGS).

[5]Wet distillers grains with solubles (WDGS).

[6]Feed ingredients as referenced from NASEM, (2016).

Chapter II: Finishing diets including Sweet Bran™ and wet distillers grains with solubles alone or in combination impact feedlot cattle performance, carcass characteristics, and rumen buffering characteristics

INTRODUCTION

Corn-milling byproducts are a widely used ingredient in beef cattle feedlot diets (Samuelson et al., 2016) to improve cattle performance and reduce cost of gain (Irwin and Good, 2013). Sweet Bran™ (SB; Cargill, Blair, NE) and wet distillers grains with solubles (WDGS) are fibrous byproducts of the corn-milling industry from the production of corn sweeteners and ethanol respectively. When used as a substitute for processed corn, cattle consuming SB exhibited either similar or greater dry matter intake (DMI), average daily gain (ADG), and gain to feed ratio (G:F) compared to cattle not consuming SB (Macken et al., 2004; Block et al., 2005; Siverson et al., 2014). In contrast, feeding WDGS has resulted in variable responses in cattle performance, as cattle consuming dry-rolled corn-based diets frequently have greater improved performance when WDGS is substituted for a portion of the diet, whereas cattle consuming steam-flaked corn-based diets may have lower performance with WDGS (Larson et al., 1993; Corrigan et al., 2009) because of differences in energy substitution between corn processing methods.

Both SB and WDGS are characteristically low in starch and are categorized as fermentable, fibrous feed ingredients that have net energy values comparable to processed corn (Stock et al., 2000). Conversely, processed grains provide a greater

proportion of energy as rapidly fermentable starch. When high concentrate diets are fed to cattle, acidotic conditions may occur from the consistent microbial production of organic acids which weakens the integrity of the ruminal wall (Nagaraja, 2018), thus limiting absorptive capacity (Owens et al., 1998), and decreasing rumen motility (Bruce and Huber, 1973). Digestive disruption caused from acidosis can result in decreased DMI (Brown et al., 2000) and performance of feedlot cattle. However, these alterations may be mitigated using strategies such as increasing the roughage concentration of the diet (Galyean and Hubbert, 2014), limiting feeding variation (Schwartzkopf-Genswein et al., 2004), or increasing roughage particle size, saliva secretion, and rumination (Allen, 1997; Weiss et al., 2017).

Physically effective NDF (peNDF) combines measurements of particle size and neutral detergent fiber (NDF) concentration to predict rumination and the extent of mechanical stimulation potentially provided by feed ingredients. Increasing the proportion of minimally processed roughage within a diet increases peNDF and stimulates greater rumination (Mertens et al., 1997; Gentry et al., 2016) and the production of saliva as a buffer (Allen, 1997). Previous research also suggests that fibrous corn-milling byproducts provide a buffering effect and increase ruminal pH (Ham et al., 1994; Montgomery et al., 2004; Siverson et al., 2014) which reduces the incidence of acidosis and increases DMI, ADG, and carcass characteristics in comparison to cattle fed no byproducts. However, corn-milling byproducts contain high concentrations of degradable fiber that are smaller in size compared to traditional roughage sources, which questions the contribution of byproducts to overall peNDF. Therefore, the objective of

this study was to characterize feedlot cattle performance, carcass characteristics, and rumen buffering characteristics when feeding Sweet Bran and/or wet distillers grain with solubles to beef finishing steers.

MATERIALS AND METHODS

Receiving Cattle Management

All procedures involving live animals were approved by the West Texas A&M University/Cooperative Research, Educational, and Extension Team Institutional Animal Care and Use Committee (approval number 2019.05.002). Before initiation of the study, a total of 478 crossbred bull and steer calves (234 ± 14.21 kg) were purchased from an order buyer in east Texas and received at the West Texas A&M University Feedlot from January 23, 2019 to April 3, 2019. During initial processing, all calves were administered a clostridial-tetanus toxoid (Calvary 9, Merck Animal Health, Madison, NJ), *Mannheimia haemolytica* bacterin (Nuplura, Elanco Animal Heath, Greenfield, IN), parenteral anthelmintic (Normectin, Norbrook Labs, Overland Park, KS), and growth-promoting implant (Component E-S with Tylan, Elanco Animal Health). Bulls were castrated via banding (Callicrate Pro, No-Bull Enterprises, St. Francis, KS) and administered meloxicam (Unichem Pharmaceuticals, Hasbrouck Heights, NJ) at 1mg/kg of body weight (BW). Calves were then used for a 56-d receiving study to compare the efficacy of using tulathromycin (Draxxin, Zoetis, Parsippany, NJ) as a metaphylactic treatment and/or administering a pentavalent respiratory vaccine (Titanium 5, Elanco Animal Health) plus re-vaccination (Unpublished Data). After completion of the receiving study,

all calves were fed a common receiving diet (Table 3) until initiation of the current study on June 12, 2019.

Animal Management and Treatments

For the present study, 455 crossbred steers were used in a randomized complete block design. Initial processing was completed over 2 consecutive d to obtain an average initial body weight (BW; 373 ± 15.5 kg) and account for differences in gut fill. On d -1 of the study, steers were weighed and re-implanted with a growth implant (Revalor XS, 40 mg estradiol and 200 mg trenbolone acetate, Merck Animal Health). On d 0, steers were allocated to 48 soil-surfaced pens (27.4 m × 6.10 m) in 12 blocks with 4 pens within block and 9 or 10 animals within a pen based on initial BW and the number of previous hospital treatments during the receiving study. Two steers from each pen were randomly selected to receive both an indwelling ruminal pH bolus (Well Cow Limited, Roslin, UK) and a 3-axis accelerometer tag (SCR, Allflex Livestock Intelligence, Madison, WI) to quantify ruminal pH and rumination for the first 92 d of the study. Within each BW block, 4 pens were randomly assigned to 1 of 4 dietary treatments (Table 3). Treatments were steam-flaked, corn-based diets containing: no corn-milling byproducts (**CON**); 20% wet distillers grains with solubles (**WDGS**), 20% Sweet Bran (**SB**); or a combination of 10% WDGS and 20% SB (**COMBO**) on a dry matter (DM)-basis. Diets were formulated to contain similar concentrations of rumen degradable protein and total fat and used 2.50% of a commercially available molasses blend as a conditioning agent to uniformly incorporate supplement and increase palatability. In preparation for this study, both SB

and WDGS were purchased in bulk from a single source, delivered, and stored in plastic silage bags on the same day to minimize the variance within each truckload that could be caused by differences in commodity blends, moisture and oil content, or added steep liquor.

Feed Delivery and Bunk Management

On the first day of the study (d 0), cattle began transition from a common receiving diet to their respective treatment diets using a two-ration system. Dietary transition was completed using a programmed transition model where cattle were fed a common receiving diet for 2 d, after which the amount of finishing diet was increased to replace 10% of the receiving diet every 2 d so that all cattle were transitioned to the final diet on d 20. Feed bunks were visually evaluated twice daily at 0630 and 1830 to determine the amount of feed to offer each pen. Bunk management was designed to allow little to no feed remaining each morning. Feed was mixed fresh daily in a stationary mixer (84-8, Roto-Mix, Dodge City, KS) and delivered to each pen beginning at 0730. The daily feed delivery order was CON, WDGS, SB, COMBO. Feed refusals were removed from the feed bunk when an excess of 2.27 kg was visually estimated during the 0630 bunk reading, weighed, and analyzed for DM in a forced-air oven (645, Precision Scientific, Chicago, IL) at 100°C for 24 h to calculate daily DMI. Performance-calculated net energy (NE; Mcal/kg) for each diet was determined using the equations: $dietary\ NEm = -b \pm \sqrt{(b^2-4ac)}/2c$ and $dietary\ NEg = 0.877 \times NEm - 0.41$, where $a = -0.41 \times$ *energy requirements for maintenance (EM; Mcal/d)*; $b = 0.877 \times EM + 0.41 \times DMI +$ *energy*

requirements for gain (EG; Mcal/d); and $c = -0.877 \times DMI$ (Zinn and Shen, 1998). The following equations were used to calculate EM and EG: $EM = 0.077 \times BW^{0.75}$, and $EG = 0.0493 \times BW^{0.75} \times ADG^{1.097}$, where $BW = average\ BW \times 0.96$ (Lofgreen and Garrett, 1968; NRC, 1984).

Data Collection and Laboratory Analysis

Samples of SB and WDGS were collected daily and composited by week for analysis of DM (100°C for 24 h), nutrient content (Servi-Tech Laboratories, Hastings, NE), and external pH. Other feed ingredients such as steam-flaked corn, corn stalks, cottonseed meal, and supplement were collected once weekly in duplicate. One sample was used to determine DM (100°C for 24 h) and adjust each diet formulation on an as-fed basis while the other was composited monthly for nutrient analysis (Servi-Tech Laboratories). Additional steam-flaked corn samples were collected from each corn delivery for analysis of total starch and starch availability (Servi-Tech Laboratories). Diet samples were collected twice weekly from the same 3 pens and split into 2 portions using a riffle splitter (H-3992, Humboldt Manufacturing Co, Elgin IL). One portion was immediately analyzed for DM (100°C for 24 h) and the second portion was composited twice per month for complete nutrient analysis by a commercial laboratory (Servi-Tech Laboratories) and measurement of external pH. The external pH of SB, WDGS, and each treatment diet was measured by mixing samples in de-ionized water before measuring with a pH meter (VWR International, Radnor, PA; FAO, 2011). Two additional fresh diet samples were collected weekly for analysis of neutral detergent fiber (NDF) and to

determine the particle size distribution of each diet using the Penn State Particle Separator (PSPS; Lammers et al., 1996; Heinrichs, 2013; Gentry et al., 2016) and to calculate peNDF. Briefly, 400 g of each diet was shaken a total of 40 repetitions though 4 screens with varying diameters (19.0, 8.0, 4.0, and 1.18 mm). The contents remaining on each tier were weighed and peNDF was calculated by multiplying the percentage of weight from the top 3 sieves by the NDF concentration of the diet and expressed as a percentage. Ruminal pH data was electronically logged in 15 min intervals. Rumination data was continuously recorded and reported as the average of rumination time within a 2 h period. Interim BW were measured at the end of the dietary transition period to differentiate the effects of dietary treatments on performance during the transition period (d 0 to 19), after the transition period (d 20 to final), and the overall finishing period (d 0 to final). Cattle were shipped to a commercial processing facility (Tyson Fresh Meats, Amarillo, TX) once the majority of cattle within a BW block were deemed to have sufficient finish to grade USDA choice and reached the target unshrunk BW of 660 kg. Similar to initial BW, final BW were calculated as the average BW over 2 consecutive days and adjusted using a 4% pencil shrink. Throughout the course of the study seven outliers were removed due to poor performance and 7 steers died from respiratory illness, bloat, or heart failure. Hot carcass weight and liver scores were collected on the day cattle were harvested and carcass data including marbling score, 12^{th}-rib fat, longissimus muscle (LM) area, kidney-heart-pelvic fat (KPH) and quality grade were collected after a 36 to 48 h chill. A common dressing percentage of 64.6% was then used to calculate carcass-adjusted performance and yield grade was calculated using the previously

described carcass measurements. All carcass data was collected by personnel from the West Texas A&M University Beef Carcass Research Center (Canyon, TX).

Statistical Analysis

Nutrient concentrations of individual feed ingredients were analyzed using the MEANS procedure of SAS (SAS Inst. Inc., Cary, NC) to describe feed ingredient variation throughout the study. Performance data and carcass data with continuous variables were analyzed as a randomized complete block design using the MIXED procedure of SAS, whereas categorical data such as liver scores and quality grade were analyzed using the GLIMMIX procedure of SAS. Pen was considered the experimental unit for all dependent variables. Diet was included in the model as a fixed variable, and block was random. Rumination and pH data presented in this study includes data recorded from d 4 to 92. Data collection was initiated on d 4 following activation and a 48-h calibration period and terminated on d 92 so each block was represented in the data set as harvest date differed by block. After collection, rumination data was managed according to methods previously described by Tomczak et al. (2019). Ruminal pH and rumination were analyzed using the MIXED procedure of SAS with repeated measures. Effects of diet, day, hour, diet × day, and diet × hour were included in the model and block was included as a random effect. The covariance structure with the smallest Akaike information criterion value was selected for each repeated variable. Ruminal pH observations that exceeded ± 2 SD of the mean were considered outliers and removed from the data set and the Kenward–Roger denominator degrees of freedom adjustment

was used when a data set contained missing samples. Treatment means were reported as least squares means ± SEM. Treatment differences were considered statistically significant when $P \leq 0.05$ and a tendency when $0.05 > P \leq 0.10$.

RESULTS

Feed Composition

The nutrient concentrations of individual feed ingredients sampled throughout the study are presented in Table 4. It is important to note that while these values were not statistically analyzed due to inherent differences among the feedstuffs used in this study, evaluating the nutrient concentrations of feed ingredients over time allows for an improved understanding of nutrient variability. Consequently, this could provide important information for nutritionists and feedlot managers making decisions regarding diet formulations and commodity management. Of particular interest is the nutrient composition of Sweet Bran and wet distillers grains with solubles, as these feedstuffs are believed to have more variable nutrient concentrations because of inconsistencies in the wet and dry milling processes used to manufacture these ingredients. The average DM, crude protein (CP), and crude fat (CF) concentrations were 60.33, 22.45, and 2.93% and 31.02, 35.35, and 10.37% for Sweet Bran and wet distillers grains with solubles, respectively. These values are similar to those reported by the NASEM (2016), although the CP concentration was slightly higher for the wet distillers grains with solubles used in this study (35.35 vs 30.63%; NASEM, 2016). Dry matter concentrations were most

variable for wet distillers grains with solubles followed by Sweet Bran, and least for cottonseed meal. Interestingly, corn stalks exhibited the greatest coefficient of variation of the ingredients used in this study for CP, CF, NEm and NEg. This could perhaps be associated with sampling error and/or high variability in the composition of corn stalks. Corn stalks were processed through a grinder before feeding to improve distribution and mixing ability, but contained a mixture of stalks, cobs, and fines. It may also be more challenging to obtain a representative sample of corn stalks because of the degree of variation in particle size and density present within the ground feed. The average total starch and starch availability of steam-flaked corn was 78.93 and 58.56%, respectively (Table 5). The starch availability reported in this study is appropriate for feedlot cattle (Schwandt et al., 2017) and ranged from a minimum of 44.0% to a maximum of 75.0%. This is important because large fluctuations in the availability of starch may contribute to metabolic disorders such as acidosis and can influence measurements of animal performance (Owens et al., 1998).

External pH of wet distillers grains with solubles was 4.42 and was greater ($P < 0.01$) than the pH of 3.85 measured for Sweet Bran (Figure 1). These pH values were similar to those reported by Firkins et al. (1985) where the pH of WDGS was 4.1 and pH of WCGF was 4.2. When examining the external pH of each treatment diet, WDGS, SB, and COMBO were lower ($P < 0.01$) than CON (Figure 2). The initial pH of byproducts are typically lower than grains because of the fermentation processes used during manufacturing and in some cases, the ensiling processes needed for preservation such as the use of bags or silos. These feedstuffs also tend to provide a larger potential buffering

capacity compared to other feed ingredients that have greater initial pH. Giger-Reverdin et al. (2001) compared methods for estimating the buffering capacity of feed ingredients by adding varying strengths of acids and bases to solution to reduce feeds. The results reported by Giger-Reverdin et al. (2001) suggest that buffering capacity is greater for WCGF in comparison to wet distillers grains with solubles and least for corn. This is an important consideration because although previous research has focused on investigating how provision of an ingredient and/or diet influences ruminal pH, little work has been completed to determine if external pH of the feedstuffs included in the diet contributes to differences in ruminal pH. The results observed in the present study agree with those reported by Giger-Reverdin et al. (2001) and indicate that simply adding a byproduct to the diet may offer a source of buffering capacity independent of changes in fermentation patterns and/or microbial populations within the rumen.

Performance and Carcass Characteristics

Initial BW and BW at the end of the transition period did not differ ($P \geq 0.85$) between dietary treatments (Table 6). However, final BW was greater ($P < 0.01$) for cattle consuming WDGS, SB, and COMBO than CON. Similarly, DMI and ADG did not differ during the transition period ($P \geq 0.44$), but DMI and ADG were greater ($P < 0.01$) for WDGS, SB, and COMBO compared to CON from both transition to final and overall. Carcass-adjusted final BW and ADG from d 0 to final were also greater ($P < 0.01$) for WDGS, SB, and COMBO compared to CON. Feed efficiency did not differ ($P \geq 0.48$) at any time throughout the feeding period nor was carcass-adjusted G:F ($P = 0.25$). No

difference in performance during the transition period likely occurred because all cattle were consuming at least a portion of their daily DMI as a common receiving diet during this time. Although the amount of each dietary treatment cattle were consuming increased during the latter half of the transition period, this may not have allowed enough time to create detectable differences in performance characteristics such as DMI and ADG. Greater DMI, ADG, and final BW of cattle consuming byproducts from transition to final and overall is generally consistent with previous studies (Macken et al., 2004; Corrigan et al., 2009; Loza et al 2010), particularly when diets used WCGF as a replacement for processed grains. In contrast, the greater DMI and ADG observed for WDGS compared to CON in the present study does not agree with Ham et al. (1994), Corrigan et al. (2009), and Depenbusch et al. (2009). Results from published work evaluating WDGS in finishing cattle diets appears to exhibit greater variability than studies completed using WCGF, but this could also be a function of differences in diet formulations between studies.

In comparison to fibrous ingredients, fermentation of concentrates increases the molar proportion of propionate in the rumen (Penner et al., 2011). In a study by Montgomery et al. (2009) lower ruminal propionate was observed as the WCGF concentration of the diet was increased from 0 to 40% of dietary DM in place of steam-flaked corn. Greater hepatic oxidation of propionate may contribute to satiety (Allen et al., 2009). Although not measured in the present study, greater concentrations of propionate as a result of increased fermentation of starch by cattle consuming the CON diet could have initiated satiety and contributed to the lower DMI. More rapid

fermentation of starch in the rumen of cattle consuming CON could have also caused feed aversion via initiation of a negative post-ingestive feedback response associated with low ruminal pH from the increased production ruminal VFA (Provenza, 1995). Alternatively, differences in DMI among treatments could be because of lower palatability of CON, possibly because of the greater DM concentration of this diet as depicted in Table 3.

Performance adjusted NEm and NEg did not differ (Table 6; $P = 0.13$) between treatments and did not differ ($P \geq 0.25$) to the energy concentrations provided by the diet. Cost of gain was greatest (Figure 3; $P < 0.01$) for CON, intermediate for WDGS and SB, and least for COMBO. Values were calculated based on average market price of the individual commodities and performance for each pen. Because the values presented here do not include additional costs such as nutritional consulting fees, labor, and/or costs associated with feed manufacturing they may appear slightly lower than what may occur in a commercial feedlot setting. The higher cost of gain for cattle consuming CON is a function of both greater feed costs and lower performance of animals consuming this diet. From this information, COMBO would be the most ideal treatment diet to feed because cattle consuming this diet perform similar to the WDGS and SB diets with a lower cost of gain.

Similar to final BW, cattle consuming WDGS, SB, and COMBO had heavier carcasses (Table 7; $P = 0.04$) than CON but dressing percentage did not differ ($P = 0.21$) among treatments, which is in agreement with previous research (Larson et al., 1993; Block et al., 2005; Loza et al., 2010). Marbling score, 12th rib fat thickness, LM area, and

the percentage of KPH fat did not differ ($P \geq 0.33$) between cattle receiving WDGS, SB, COMBO, or CON. A tendency ($P = 0.09$) for greater yield grade for WDGS, SB, and COMBO than CON likely occurred because of the greater HCW of cattle consuming the byproduct diets, as HCW is a variable in the yield grade equation (USDA, 2017). Quality grade and liver abscess scores were not different ($P \geq 0.27$) among treatments. However, the proportion of abscessed livers was numerically greater for CON than any of the byproduct diets. Liver abscesses have been linked to intensive feeding strategies and believed to be caused from rumenitis. Rumenitis causes damage to the rumen epithelium and allows bacteria from ruminal contents, such as *Fusobacterium necrophorum* and *Trueperella pyogenes,* to enter the hepatic portal blood and invade and colonize the liver resulting in the formation of an abscess (Nagaraja and Chengappa, 1998). Haskins et al. (1967) demonstrated that liver abscess are more pronounced when cattle are fed highly-fermentable concentrate diets such as the CON diet used in the present study. However, abscess prevalence can be reduced by increasing the dietary inclusion of fiber which can dilute available starch and stimulate greater rumination (Reinhardt and Hubbert, 2015) such as what occurred in cattle consuming the byproduct diets. The numerical difference in liver abscesses observed in this study is a particularly interesting trend because it is historically challenging to delineate differences among treatments for binomial outcomes such as the proportion of liver abscesses in small pen research. Because liver abscesses occur at low frequencies, a statistical difference between treatments may have been observed with a greater number of samples or pen replications.

Physically Effective NDF

As a function of the greater inclusion rate of fibrous byproducts in the diet, neutral detergent fiber (NDF) concentrations (Table 8) were greatest ($P < 0.01$) for COMBO, intermediate for WDGS and SB, and least for CON. No differences ($P = 0.10$) were observed among treatment diets for the proportion of particles > 19.0 mm because the top screen of the PSPS primarily captures corn stalk particles (Jennings et al., 2020) which were formulated in all diets at a continuous inclusion of 8.0% of DM. The proportion of particles retained on the 8.0 mm screen were lowest ($P < 0.01$) for COMBO, intermediate for WDGS and SB, and least for CON. In contrast, the percentage of particles retained on the 4.0 mm screen was greater ($P < 0.01$) for SB, COMBO, and CON than WDGS. Similar to the 8.0 mm screen, a large proportion of Sweet Bran is retained on the 4.0 mm screen. The proportion of diet retained on the 1.18 mm screen was greatest ($P < 0.01$) for COMBO, intermediate for WDGS and SB, and least for CON. Although not measured in the present study, the smaller particle size of wet distillers grains with solubles particles compared to Sweet Bran decreased the retention of WDGS on the 4.0 mm screen in comparison to SB and increased retention on the 1.18 mm screen. The 1.18 mm screen was used as an additional measure for this study not reported in the work completed by Jennings et al. (2020) or Gentry et al. (2016) to further characterize the smaller particle size of byproducts (Yang and Beauchemin, 2006a). Overall, the percentage of particles that measured > 4.0 mm was greatest ($P < 0.01$) for CON, intermediate for SB, and lowest for COMBO and WDGS.

During this study, we did not determine the particle size for each ingredient included in the diet. However, Jennings et al. (2020) reported the distribution of particle size for individual ingredients such as corn stalks, Sweet Bran, and steam-flaked corn. The majority of corn stalks were captured on the 19.0 mm screen and 64.1% of the particles were > 4.0 mm. In contrast, the greatest proportion of both Sweet Bran and steam-flaked corn particles were retained on the 8.0 mm screen (38.1 and 72.3% of retained particles for Sweet Bran and steam-flaked corn respectively). However, steam-flaked corn contained a greater proportion of particles larger than > 4.0 mm (88.0%) compared to both Sweet Bran (69.0%) and corn stalks (64.1%). Cardoza (1985) identified that particles larger than > 4.0 mm are important stimulators of ruminal contractions and rumination activity. However, although the proportion of particles > 4.0 mm for Sweet Bran and corn stalks reported by Jennings et al. (2020) was similar, it is unlikely that Sweet Bran stimulates rumination to the same extent as a traditional roughage source such as corn stalks, particularly when corn stalks contain a greater proportion of particles larger than 19.0 mm. Furthermore, although steam-flaked corn also contains a large portion of particles greater than > 4.0 mm, it is not considered a fiber source and likely contributes minimally to rumination activity because of the high proportion of rapidly fermentable starch. Therefore, additional measurements such as peNDF provide a unique opportunity to characterize feed ingredients because peNDF combines elements of both the physical and chemical characteristics of feeds.

Physically effective NDF has historically been used to evaluate fibrous ingredients such as roughages, however there is limited research which discusses the

interactions between fibrous byproducts and NDF concentration, particle size, peNDF, rumination, and ruminal pH. This is further complicated when evaluating feedlot diets which have characteristically low roughage concentrations. However, peNDF was greatest ($P < 0.01$) for COMBO and SB followed by WDGS and CON. Despite the highest proportion of particles > 4.0 mm, the CON diet had the lowest peNDF because it also contained the lowest NDF concentration. Because WDGS and SB had similar NDF concentrations, the difference in particle size between WDGS and SB (± 5.4%) influenced peNDF by ± 1.0%. In addition, WDGS and COMBO had the same proportion of particles > 4.0 mm. Therefore, the difference in NDF concentration (± 2.9%) changed peNDF by ± 1.3%. Furthermore, peNDF does not change when particle size is decreased by 6.7% and NDF is increased by 2.9% based on the observed differences between COMBO and SB. Therefore, based on these assumptions, differences in NDF concentration will have a stronger influence on peNDF than a change in particle size which agrees with other studies (Gentry et al., 2016; Weiss et al., 2017). This relationship also describe the peNDF concentration of CON (greater particle size and lower NDF). In addition, other studies which also support that particle size has a greater influence on peNDF use less screens when reporting data (Plaizier, 2004; Yang and Beauchemin, 2006b) which may underestimate the peNDF contributions that would have been obtained by using smaller screens. Variations in shaking methods and calculating peNDF are summarized by Plaizier, (2004). This is an important consideration for feedlot diets containing byproducts because although the particle size of these ingredients may not be as physically effective as traditional roughage sources, the greater NDF concentration

increases peNDF concentration of the diet when fibrous byproducts are used to replace processed grains.

Rumination

Daily rumination minutes for cattle consuming CON, WDGS, SB, and COMBO are presented in Figure 4. It should be noted that the sharp decrease in rumination depicted on d 39 occurred because of technological problems with the data logging equipment and resulted in lower rumination compared to other days included in the collection period. A diet × day interaction ($P < 0.01$) was observed for daily rumination minutes. On d 17 cattle consuming SB had the greatest rumination, WDGS and CON were intermediate, and COMBO was least. Similarly, on d 26 SB was the greatest, CON was intermediate, and the lowest rumination was reported for COMBO and WDGS. On d 42 and 47, rumination was greatest for SB and COMBO, intermediate for WDGS, and least for CON. Daily rumination was greatest for COMBO and WDGS, intermediate for SB, and least for CON on d 51. On d 52 and 59, rumination time was greatest for COMBO, intermediate for SB and WDGS, and least for CON. Cattle receiving COMBO, WDGS, and SB had greater rumination than CON on d 66. On d 71, daily rumination min were greatest for WDGS and COMBO, intermediate for SB, and least for CON. These results suggest that generally when diet × day interactions occurred, the cattle consuming CON ruminated less than those receiving diets containing grain-milling byproducts.

Although the main effect of diet was not statistically significant ($P = 0.39$), cattle consuming SB spent the most time ruminating per day followed by COMBO, WDGS, and CON (460, 442, 436, and 410 minutes respectively; Table 9). This suggests that the byproduct source could influence rumination to a small degree and that the greater particle size of Sweet Bran vs. wet distillers grains distillers may possibly explain the numerically greater rumination observed for cattle consuming SB and COMBO in comparison to WDGS. Particle sizes > 4.0 mm stimulate rumination (Cardoza, 1985). However, even though the proportion of particles > 4.0 mm was highest for CON, this did not result in greater rumination min per day as the greater particle size can be attributed to a higher proportion of steam-flaked corn pieces with a larger diameter than either byproduct. Therefore, the greater overall peNDF contribution of the fibrous byproducts in SB and COMBO may explain differences in daily rumination min compared to CON.

Alternatively, another likely explanation for the lower daily rumination for CON described in the present study is the lower DMI of cattle receiving CON compared to WDGS, SB, and COMBO (9.10 vs. 9.72, 9.76, and 9.64 kg of DMI respectively) because rumination is influenced by DMI (Welch and Smith, 1969, Bae et al., 1981). When evaluated as a function of DMI, the effects of diet on daily rumination min become less consistent. A diet × day interaction (Figure 5; $P < 0.01$) was observed for daily rumination per kg of DM. On d 26 rumination per kg of DM was least for WDGS, intermediate for COMBO, and greatest for CON, but SB did not differ from CON, WDGS, or COMBO. On d 28, time spent ruminating per kg of DM was greatest for SB,

intermediate for CON and least for COMBO and WDGS. On d 35, rumination per kg of DM was least for COMBO and WDGS, intermediate for SB, and greatest for CON, whereas rumination on d 36 was least for COMBO, intermediate for WDGS and SB, and greatest for CON. On d 40, daily rumination min per kg of DM were greatest for SB, intermediate for CON, and least for WDGS and COMBO. On d 47, time spent ruminating was greatest for COMBO, intermediate for SB and CON, and least for WDGS. Daily rumination minutes per kg of DM were 48.41, 48.83, 46.77, and 45.50 for SB, COMBO, CON, and WDGS ($P = 0.81$). Interestingly, although rumination per kg of DM follows a similar numerical trend as overall daily rumination min, the magnitude of difference between treatments is lower. This suggests that at least a portion of the difference in daily rumination min can be attributed to changes in DMI.

A diet × day interaction (Figure 6; $P < 0.01$) was detected for rumination minutes per kg of NDF intake where WDGS, SB, and COMBO were lower than CON on d 4, 6, 14, 15, 20 to 25, 41 to 56, 58 to 65, 67 to 69, 74, 75, 77, 81, 82, 84, 85, and 87. On d 11 to 13, 16, 18, 19, 26, 31, 32, and 34 to 37 rumination was greatest for CON, intermediate for SB and WDGS, and lowest for COMBO, but WDGS did not differ from COMBO. On d 5, 7, 9, 10, 90, and 91 rumination was least for COMBO, intermediate for SB and WDGS, and greatest for CON. However, on d 8 CON had greater rumination than WDGS and COMBO but SB was not different than CON or WDGS. Rumination was greatest for CON, intermediate for WDGS, and least for COMBO on d 17, while SB was not different from WDGS or COMBO. On d 27, 33, and 38 rumination per kg of NDF was greatest for CON, intermediate for SB, and least for WDGS and COMBO. In

contrast, CON and SB had greater rumination per kg of NDF than WDGS and COMBO on d 28 to 30 and 40. On d 57, CON had the greatest rumination followed by WDGS, SB, and COMBO, but WDGS was not different from SB and COMBO. On d 66, 71, 76, and 77 CON had greater rumination than COMBO, but WDGS and SB did not differ. On d 70, 73, 79, and 83 CON had greater rumination than WDGS and COMBO but was not different than SB. Cattle consuming CON had greater rumination than SB and COMBO but WDGS did not differ on d 72, 80, and 86. Overall, steers consuming CON ruminated the most (min/kg NDF) in comparison to SB, WDGS, and COMBO ($P < 0.01$).

Although SB, WDGS, and COMBO contained greater proportions of NDF compared to CON, the NDF in CON was primarily provided by the corn stalks in the diet. Because corn stalks have a larger particle size and greater peNDF compared to fibrous byproducts such as Sweet Bran (Gentry et al., 2016), this stimulated rumination to a greater extent when expressed per unit of dietary fiber intake. Alternatively, because low ruminal pH negatively impacts fibrolytic bacterial species (Kezar and Church, 1979), lower ruminal pH resulting from more rapid fermentation of the additional starch provided by CON may have impacted fiber degradation such that increased rumination was required to compensate for lower NDF digestion and reduce particle size to allow passage to the omasum (Fox and Tedeschi, 2002).

A diet × day interaction (Figure 7; $P < 0.01$) was also observed for rumination per kg of peNDF. Rumination was lower for SB and COMBO than CON on d 4 to 6, 22, 24, 50, 64, and 89. On d 8, 10 to 15, 17 to 19, 25, 30 to 32, 46, 62, 63, 65, 68, 75, 76, and 91 rumination per kg of peNDF was lower for COMBO than CON and WDGS than CON on

d 16, 21, 33, 49, and 57. Alternatively, on d 5 rumination per kg of peNDF was least for COMBO, intermediate for SB, and greatest for CON while WDGS was not different from SB and CON. On d 9, rumination per kg of peNDF was least for COMBO and greatest for WDGS and CON but SB did not differ. On d 28 and 29, rumination per kg of peNDF was lower for COMBO and SB than CON, whereas rumination was greater for WDGS, SB, and COMBO than CON on d 26, 27, 35 to 38, 55, and 56. On d 90, WDGS ruminated the greatest per kg of peNDF, and COMBO was least, but SB and CON were not, different from WDGS and COMBO. Daily rumination minutes per kg of peNDF were 507, 458, 442, and 418 for CON, WDGS, SB, and COMBO ($P = 0.02$). Because the peNDF in CON was provided primarily by the corn stalks in the diet, this suggests that the peNDF from forage-based ingredients stimulates rumination to a greater extent than fibrous byproducts. Although the byproduct diets contained a greater proportion of peNDF, this was primarily a function of increased NDF concentration and implies that particle size may be a greater stimulus of rumination than overall fiber concentration of the diet.

Circadian rumination minutes from d 0 to the end of transition, transition to final, and overall are presented in Figure 8, 9, and 10. Hourly patterns in rumination within day are consistent with those reported by Tomczak et al. (2019) and can primarily be related to changes in the activity of cattle throughout the day. For example, Tomczak et al. (2019) explained that rumination is lowest when cattle are eating such as after feeding (0600 to 1000 h) and during peak activity such as at dusk (1600 to 2000 h), which is also supported by Stricklin and Kautz-Scanavy (1984). In contrast, rumination is greatest

during the night from 2000 to 0400 h. During the transition period, circadian rumination activity was not different ($P = 0.42$) between dietary treatments because cattle were consuming a large proportion of a common receiving diet for the majority of the collection period. A diet × hour interaction ($P < 0.01$) was observed for circadian rumination minutes from the end of transition to final. Rumination was greater for SB, WDGS, and COMBO in comparison to CON diet at 0800 h and greatest for COMBO, intermediate for SB and WDGS, and least for CON at 1000 h. A similar diet × hour interaction was also observed for overall rumination which was greater for SB, WDGS, and COMBO in comparison to the CON diet at 0800 h and greatest for COMBO, intermediate for SB and WDGS, and least for CON at 1000 h. Feeding began each day 0730 and CON was the first diet delivered, therefore it is possible that the lower rumination of CON from 0600 to 0800 h could have been impacted by time of intake. Tomczak et al. (2019) demonstrated that rumination is inversely related to activity. Cattle are creatures of habit, and therefore it is a common visual observation in feedlots to see cattle moving towards and standing at the feed bunk immediately before feeding if fed at the same time each day. If CON cattle had greater activity immediately before feeding, this could explain the lower rumination of CON as it is likely that only cattle receiving CON were fed during the 2 h time interval from 0600 to 0800 h. However, the lower rumination of CON continued from 0800 to 1000 h when the other treatment diets were fed, suggesting that CON cattle did have lower rumination in the hours immediately preceding and following feeding. Parsons et al. (2007) reported that cattle consuming a steam-flaked, corn-based diet have more aggressive feeding behavior in comparison to

cattle consuming byproducts and will consume a larger meal during the first feeding event. The aggressive behavior may also suggest cattle are active and waiting at the bunk earlier in the day and therefore not ruminating which could explain the lower rumination of CON.

Ruminal pH

Daily ruminal pH values were 5.78, 5.69, 5.63 and 5.47 for COMBO, SB, WDGS, and CON respectively (Figure 11). Ruminal pH was greatest for COMBO, intermediate for WDGS, and lowest for CON, whereas SB was greater than CON but not different from WDGS and COMBO ($P < 0.01$). Decreasing the concentration of dietary starch will increase pH (Firkins et al., 1985; Krehbiel et al., 1995). Montgomery et al. (2004) and Corrigan et al. (2009) also reported greater pH is observed when a portion of the corn in the diet is replaced with Sweet Bran and/or wet distillers grains with solubles. The COMBO diet contained the lowest proportion of steam-flaked corn, which likely explains the greater pH in COMBO because of less available starch in the diet and a greater potential buffering capacity from the higher byproduct inclusion rate (30% total byproduct). However, although pH of COMBO was greater than WDGS, no difference between COMBO and SB suggests that adding wet distillers grains with solubles to diets already containing Sweet Bran may not provide additional pH modulation beyond that achieved when 20% of dietary DM is provided as Sweet Bran.

Similar to circadian rumination minutes, hourly ruminal pH during transition, from transition to final, and overall is represented in Figure 12, 13, and 14. Hourly changes in ruminal pH throughout the day represent increases or decreases in the fermentation of substrates and mirror consumption patterns. Circadian ruminal pH increased from 2200 to 1000 h, which reflects a 0730 feeding time, then decreases from 1000 to 1400 h as ruminal fermentation of nutrients increases after feeding and rumen microbes produce VFA's as a byproduct of nutrient metabolism (Hungate, 1966). The lowest ruminal pH was observed during the 2 h time period from 2000 to 2200 h, which is approximately 12 h after peak ruminal pH (1000 h) and agrees with Campanili et al. (2017).

There was a diet × hour effect ($P = 0.02$) for circadian ruminal pH during the transition period where COMBO had the greatest pH, SB was intermediate, and WDGS and CON were least at 1200 h. Ruminal pH at 1400 h was greatest for COMBO, intermediate for SB and WDGS, and lowest for CON. From transition to final a diet × hour interaction was also observed ($P < 0.01$) for circadian ruminal pH where COMBO and SB were greatest, WDGS was intermediate, although not different than SB and COMBO, and CON the least at 1000 h. From 1200 to 1600 h, ruminal pH was greatest for COMBO, intermediate for SB, and WDGS and lowest for CON. At 1800 h, COMBO, SB, and WDGS were all greater than CON and COMBO was greatest, SB and WDGS were intermediate, and CON was least at 2000 h. A similar pattern for diet × hour ($P < 0.01$) was also observed for overall circadian ruminal pH. Differences began at 0800 h where ruminal pH for COMBO was greater than WDGS and CON. At 1000 h circadian

ruminal pH for COMBO was greatest, SB and WDGS were intermediate, and ruminal pH was lowest for CON. At 1200 and 1600 h ruminal pH was greater for COMBO, WDGS, and SB than CON. Circadian ruminal pH for COMBO was also greater at 1400 h, while ruminal pH of cattle consuming SB and WDGS was intermediate and lowest for CON. At 1600 h ruminal pH for COMBO, SB, and WDGS was greater than CON. At 1800 h, pH of COMBO and WDGS was greatest, SB was intermediate, and CON was least. From 2000 to 2200 h COMBO was greatest, SB and WDGS were intermediate, and circadian pH was least for CON. Generally, these results suggest that after feeding ruminal pH is greatest for COMBO, followed by SB and WDGS, and lowest for CON.

Differences among treatments for ruminal pH were most pronounced after the dietary transition period when cattle were consuming their entire allotment of feed as the individual dietary treatments. While differences in rumination between treatments occurred primarily around feeding each day, differences in hourly ruminal pH were most pronounced after feeding when peak fermentation likely occurred. This suggests that the pH modulation that occurred for the byproduct diets in the present study was most likely facilitated by the greater proportion of fibrous ingredients and displacement of starch in the diet provided by COMBO, SB, and WDGS than as a result of additional buffering capacity from increased saliva production during rumination. The CON diet included the greatest proportion of steam-flaked corn followed by WDGS and SB, and COMBO. Therefore, the greater pH observed in cattle consuming COMBO compared to SB and WDGS can also be attributed to the overall greater byproduct concentration of the diet and a lower proportion of rapidly fermentable starch (Owens et al., 1998) which may

have caused acidotic conditions for an extended period of the day (Figure 14) which could be related to decreased DMI of the CON cattle.

CONCLUSIONS

Corn-milling byproducts from the manufacturing of corn sweetener and ethanol manufacturing serve as high energy, fibrous feed ingredients that can replace a portion of the processed grains in feedlot cattle diets. The competitive cost in comparison to corn and improved performance associated with fibrous, corn-milling byproduct use maximizes cost of gain. Results of the present study suggest that while replacing a portion of steam-flaked corn in the diet with fibrous, corn-milling byproducts is advantageous; SB, WDGS, and COMBO result in similar improvements in cattle performance. In addition to improving cattle performance, corn-milling byproducts contribute a significant amount of NDF and peNDF to the diet and may improve rumen health. Rumination per kg of DMI is not different but there was observed improvement of ruminal pH of the diets containing fibrous byproducts and lower starch concentration which may potentially mitigate ruminal acidosis. However, because byproducts are not traditional roughage sources, additional research is needed to further characterize these feed ingredients and determine the physical contribution of byproducts to rumen integrity and functionality.

LITERATURE CITED

Allen, M. S. 1997. Relationship between fermentation acid production in the rumen and the requirement for physically effective fiber. J. Dairy Sci. 80(7):1447-1462. doi: 10.3168/jds.s0022-0302(97)76074-0

Bae, D. H., J. G. Welch, and A. M. Smith. 1981. Efficiency of mastication in relation to hay intake by cattle. J. Anim. Sci. 52(6):1371-1375. doi: 10.2527/jas1981.5261371x

Balthrop, J., B. Brand, R. Cowie, J. Danier, J. de Boever, L. de Jonge, F. Jackson, H. P. Makkar, and C. Piotrowski. 2011. Quality assurance for animal feed analysis laboratories. FAO

Block, H. C., C. N. Macken, T. J. Klopfenstein, G. E. Erickson, and R. A. Stock. 2005. Optimal wet corn gluten and protein levels in steam-flaked corn-based finishing diets for steer calves. J. Anim. Sci. 83(12):2798-2805. doi: 10.2527/2005.83122798x

Brown, M. S., C. R. Krehbiel, M. L. Galyean, M. D. Remmenga, J. P. Peters, B. Hibbard, J. Robinson, and W. M. Moseley. 2000. Evaluation of models of acute and subacute acidosis on dry matter intake, ruminal fermentation, blood chemistry, and endocrine profiles of beef steers. J. Anim. Sci. 78(12):3155-3168. doi: 10.2527/2000.78123155x

Bruce, L. A., and T. L. Huber. 1973. Inhibitory effect of acid in the intestine on rumen motility in sheep. J. Anim. Sci. 37(1):164-168. doi: 10.2527/jas1973.371164x

Campanili, P. R. B., J. O. Sarturi, M. A. Ballou, S. J. Trojan, J. D. Sugg, L. A. Ovinge, A. U. Alrumaih, L. A. Pellarin, and A. A. Hoffman. 2017. Effects of silage type and inclusion level on ruminal characteristics and feeding behavior of steers fed finishing diets. J. Anim. Sci. 95(10):4623-4637. doi: 10.2527/jas2017.1510

Cardoza, R. 1985. Threshold size and factors affecting fecal particle weight distribution. Masters. Univ. of Georgia, Athens.

Corrigan, M. E., G. E. Erickson, T. J. Klopfenstein, M. K. Luebbe, K. J. Vander Pol, N. F. Meyer, C. D. Buckner, S. J. Vanness, and K. J. Hanford. 2009. Effect of corn processing method and corn wet distillers grains plus solubles inclusion level in finishing steers. J. Anim. Sci. 87(10):3351-3362. doi: 10.2527/jas.2009-1836

Depenbusch, B. E., J. S. Drouillard, E. R. Loe, J. J. Higgins, M. E. Corrigan, and M. J. Quinn. 2008. Efficacy of monensin and tylosin in finishing diets based on steam-flaked corn with and without corn wet distillers grains with solubles. J. Anim. Sci. 86(9):2270-2276. doi: 10.2527/jas.2007-0017

Firkins, J. L., L. L. Berger, and G. C. Fahey, Jr. 1985. Evaluation of wet and dry distillers grains and wet and dry corn gluten feeds for ruminants. J. Anim. Sci. 60(3):847-860. doi: 10.2527/jas1985.603847x

Fox, D., and L. Tedeschi. 2002. Application of physically effective fiber in diets for feedlot cattle. In: Proceedings of the plains nutrition conference. p 67.

Galyean, M., and M. Hubbert. 2014. Traditional and alternative sources of fiber—Roughage values, effectiveness, and levels in starting and finishing diets. Prof. Anim. Sci. 30(6):571-584. doi: 10.15232/pas.2014-01329

Gentry, W. W., C. P. Weiss, C. M. Meredith, F. T. McCollum, N. A. Cole, and J. S. Jennings. 2016. Effects of roughage inclusion and particle size on performance and rumination behavior of finishing beef steers. J. Anim. Sci. 94(11):4759-4770. doi: 10.2527/jas.2016-0734

Giger-Reverdin, S., C. Duvaux-Ponter, D. Sauvant, O. Martin, I. N. do Prado, and R. Müller. 2002. Intrinsic buffering capacity of feedstuffs. Anim. Feed Sci. Technol. 96(1-2):83-102. doi: 10.1016/s0377-8401(01)00330-3

Ham, G. A., R. A. Stock, T. J. Klopfenstein, E. M. Larson, D. H. Shain, and R. P. Huffman. 1994. Wet corn distillers byproducts compared with dried corn distillers grains with solubles as a source of protein and energy for ruminants. J. Anim. Sci. 72(12):3246-3257. doi: 10.2527/1994.72123246x

Haskins, B. R., M. B. Wise, H. B. Craig, and E. R. Barrick. 1967. Effects of levels of protein, sources of protein and an antibiotic on performance, carcass characteristics, rumen environment and liver abscesses of steers fed all-concentrate rations. J. Anim. Sci. 26(2):430-434. doi: 10.2527/jas1967.262430x

Heinrichs, A., and P. Kononoff. 2013. The Penn State particle separator. Penn State Extension, University Park, PA. DSE 2013(186):1-8.

Hungate, R. E. 1966. The rumen and its microbes. Elsevier

Irwin, S., and D. Good. 2013. Understanding the pricing of distillers' grain solubles. In: farmdoc daily. Rep. No. (3)133. Department of Agriculture and Consumer Economics, University of Illinios Urbana-Champaign. p. 1-3

Jennings, J., C. Lockard, L. Tedeschi, and T. Lawrence. 2020. Effects of corn stalk inclusion rate on rumination and ruminal pH in finishing beef steers. Appl. Anim. Sci. 36(3):377-388. doi: 10.15232/aas.2019-01947

Kezar, W. W., and D. C. Church. 1979. Ruminal changes during the onset and recovery of induced lactic acidosis in sheep. J. Anim. Sci. 49(5):1161-1167. doi: 10.2527/jas1979.4951161x

Krehbiel, C. R., R. A. Stock, D. W. Herold, D. H. Shain, G. A. Ham, and J. E. Carulla. 1995. Feeding wet corn gluten feed to reduce subacute acidosis in cattle. J. Anim. Sci. 73(10):2931-2939. doi: 10.2527/1995.73102931x

Lammers, B., D. Buckmaster, and A. J. Heinrichs. 1996. A simple method for the analysis of particle sizes of forage and total mixed rations. J. Dairy Sci. 79(5):922-928. doi: 10.3168/jds.s0022-0302(96)76442-1

Larson, E., R. Stock, T. Klopfenstein, M. Sindt, and R. Huffman. 1993. Feeding value of wet distillers byproducts for finishing ruminants. J. Anim. Sci. 71(8):2228-2236. doi: 10.2527/1993.7182228x

Lofgreen, G. P., and W. N. Garrett. 1968. A system for expressing net energy requirements and feed values for growing and finishing beef cattle. J. Anim. Sci. 27(3):793-806. doi: 10.2527/jas1968.273793x

Loza, P. L., C. D. Buckner, K. J. Vander Pol, G. E. Erickson, T. J. Klopfenstein, and R. A. Stock. 2010. Effect of feeding combinations of wet distillers grains and wet corn gluten feed to feedlot cattle. J. Anim. Sci. 88(3):1061-1072. doi: 10.2527/jas.2009-2190

Macken, C. N., G. E. Erickson, T. J. Klopfenstein, and R. A. Stock. 2004. Effects of concentration and composition of wet corn gluten feed in steam-flaked corn-based finishing diets. J. Anim. Sci. 82(9):2718-2723. doi: 10.2527/2004.8292718x

Mertens, D. 1997. Creating a system for meeting the fiber requirements of dairy cows. J. Dairy Sci. 80(7):1463-1481. doi: 10.3168/jds.s0022-0302(97)76075-2

Montgomery, S. P., J. S. Drouillard, E. C. Titgemeyer, J. J. Sindt, T. B. Farran, J. N. Pike, C. M. Coetzer, A. M. Trater, and J. J. Higgins. 2004. Effects of wet corn gluten feed and intake level on diet digestibility and ruminal passage rate in steers. J. Anim. Sci. 82(12):3526-3536. doi: 10.2527/2004.82123526x

Nagaraja, T. G. 2018. Ruminal epithelial integrity and liver abscesses in feedlot cattle. J. Anim. Sci. 96(suppl_2):218-219. doi: 10.1093/jas/sky073.404

Nagaraja, T. G., and M. M. Chengappa. 1998. Liver abscesses in feedlot cattle: a review. J. Anim. Sci. 76(1):287-298. doi: 10.2527/1998.761287x

NRC. 1984. Nutrient requirements of beef cattle. 6th rev. ed. National Academies Press.

NRC. 1988. Nutrient requirements of dairy cattle, 6th rev. ed. Nat. Acad. Sci., Washington, DC.

NASEM (National Academics of Science, E., and Medicine.). 2016. Nutrient requirements of beef cattle. 8th rev. ed. Natl. Acad. Press, Washington, DC.

Allen, M. S., B. J. Bradford, and M. Oba. 2009. BOARD-INVITED REVIEW: The hepatic oxidation theory of the control of feed intake and its application to ruminants. J. Anim. Sci. 87(10):3317-3334. doi: 10.2527/jas.2009-1779

Owens, F. N., D. S. Secrist, W. J. Hill, and D. R. Gill. 1998. Acidosis in cattle: a review. J. Anim. Sci. 76(1):275-286. doi: 10.2527/1998.761275x

Parsons, C. H., J. T. Vasconcelos, R. S. Swingle, P. J. Defoor, G. A. Nunnery, G. B. Salyer, and M. L. Galyean. 2007. Effects of wet corn gluten feed and roughage levels on performance, carcass characteristics, and feeding behavior of feedlot cattle. J. Anim. Sci. 85(11):3079-3089. doi: 10.2527/jas.2007-0149

Penner, G. B., M. A. Steele, J. R. Aschenbach, and B. W. McBride. 2011. Ruminant nutrition symposium: Molecular adaptation of ruminal epithelia to highly fermentable diets. J. Anim. Sci. 89(4):1108-1119. doi: 10.2527/jas.2010-3378

Plaizier, J. 2004. Replacing chopped alfalfa hay with alfalfa silage in barley grain and alfalfa-based total mixed rations for lactating dairy cows. J. Dairy Sci. 87(8):2495-2505

Provenza, F. D. 1995. Postingestive feedback as an elementary determinant of food preference and intake in ruminants. J. Range Manage. 48(1):2-17. doi: 10.2307/4002498

Reinhardt, C., and M. Hubbert. 2015. Control of liver abscesses in feedlot cattle: A review. Prof. Anim. Sci. 31(2):101-108. doi: 10.15232/pas.2014-01364

Samuelson, K. L., M. E. Hubbert, M. L. Galyean, and C. A. Löest. 2016. Nutritional recommendations of feedlot consulting nutritionists: The 2015 New Mexico State and Texas Tech University survey. J. Anim. Sci. 94(6):2648-2663. doi: 10.2527/jas.2016-0282

Schwandt, E., M. Hubbert, D. Thomson, C. Vahl, S. Bartle, and C. Reinhardt. 2016. A survey of starch availability of steam-flaked corn in commercial feedlots evaluating roll size and flake density. Prof. Anim. Sci. 32(5):550-560. doi: 10.15232/pas.2015-01496

Schwartzkopf-Genswein, K. S., K. A. Beauchemin, T. A. McAllister, D. J. Gibb, M. Streeter, and A. D. Kennedy. 2004. Effect of feed delivery fluctuations and feeding time on ruminal acidosis, growth performance, and feeding behavior of feedlot cattle. J. Anim. Sci. 82(11):3357-3365. doi: 10.2527/2004.82113357x

Siverson, A. V., E. C. Titgemeyer, S. P. Montgomery, B. E. Oleen, G. W. Preedy, and D. A. Blasi. 2014. Effects of corn processing and dietary wet corn gluten feed inclusion on performance and digestion of newly received growing cattle. J. Anim. Sci. 92(4):1604-1612. doi: 10.2527/jas.2013-6839

Stock, R. A., J. M. Lewis, T. J. Klopfenstein, and C. T. Milton. 2000. Review of new information on the use of wet and dry milling feed by-products in feedlot diets. J. Anim. Sci. 77(suppl_E):1-12. doi: 10.2527/jas2000.77E-Suppl1w

Stricklin, W., and C. Kautz-Scanavy. 1984. The role of behavior in cattle production: a review of research. Applied Animal Ethology 11(4):359-390

Tomczak, D. J., C. L. Lockard, J. S. Jennings, and J. T. Richeson. 2019. Performance, rumination, and rumen pH responses to different dietary energy density and feed management strategies in auction-derived feedlot cattle. J. Anim. Sci. 97(11):4682-4690. doi: 10.1093/jas/skz323

USDA. 2017. United States standards for grades of carcass beef. In: No. (82)116. Agricultural Marketing Service. p. 27782-27786

Weiss, C. P., W. W. Gentry, C. M. Meredith, B. E. Meyer, N. A. Cole, L. O. Tedeschi, F. T. McCollum, III, and J. S. Jennings. 2017. Effects of roughage inclusion and particle size on digestion and ruminal fermentation characteristics of beef steers. J. Anim. Sci. 95(4):1707-1714. doi: 10.2527/jas.2016.1330

Welch, J., and A. Smith. 1970. Forage quality and rumination time in cattle. J. Dairy Sci. 53(6):797-800. doi: 10.3168/jds.s0022-0302(70)86293-2

Yang, W., and K. Beauchemin. 2006a. Physically effective fiber: Method of determination and effects on chewing, ruminal acidosis, and digestion by dairy cows. J. Dairy Sci. 89(7):2618-2633. doi: 10.3168/jds.s0022-0302(06)72339-6

Yang, W., and K. Beauchemin. 2006b. Increasing the physically effective fiber content of dairy cow diets may lower efficiency of feed use. J. Dairy Sci. 89(7):2694-2704. doi: 10.3168/jds.s0022-0302(06)72345-1

Zinn, R. A., and Y. Shen. 1998. An evaluation of ruminally degradable intake protein and metabolizable amino acid requirements of feedlot calves. J. Anim. Sci. 76(5):1280-1289. doi: 10.2527/1998.7651280x

Table 3. Ingredient composition and nutrient analysis of finishing diets including no fibrous corn-milling byproducts, wet distillers grains with solubles, and/or Sweet Bran

		Treatments			
Item	REC[1]	CON	WDGS	SB	COMBO
Ingredient, % of DM					
Corn Grain, Flaked	28.54	76.55	63.92	62.55	53.22
Sweet Bran	42.00	-	-	20.00	20.00
WDGS[2]	-	-	20.00	-	10.00
Corn Stalks	19.00	8.00	8.00	8.00	8.00
Cottonseed Meal	-	6.00	-	-	-
Corn Oil	-	2.45	1.08	2.45	1.78
Molasses Blend[3]	7.00	2.50	2.50	2.50	2.50
Receiving Supplement[4]	3.46	-	-	-	-
Finishing Supplement[5]	-	4.50	4.50	4.50	4.50
Nutrient Composition, DM basis[6]					
DM, %	70.80	82.90	63.20	74.90	66.30
TDN, %[7]	74.40	90.00	89.10	89.10	87.90
CP, %	15.00	13.50	15.90	13.60	15.10
RDP, %	9.47	7.90	7.68	8.57	8.26
RUP, %	5.53	5.59	8.22	5.03	6.84
Crude Fat, %	3.30	5.30	5.30	5.50	5.50
Ca, %	0.97	0.65	0.78	0.72	0.93
P, %	0.55	0.32	0.39	0.39	0.47
Total Starch, %	30.00	58.30	51.10	51.50	46.70
ME, Mcal/kg[8]	2.68	3.26	3.21	3.21	3.17
NEm, Mcal/kg[9]	1.78	2.22	2.20	2.22	2.18
NEg, Mcal/kg[10]	1.14	1.54	1.54	1.52	1.50

[1]Receiving diet used during preceding animal health study (Unpublished Data) and transition period.

[2]Wet Distillers Grains with Solubles (WDGS).

[3]72 Brix Molasses Blend (Westway Feed Products LLC, Hereford, Texas).

[4]Formulated to meet or exceed NASEM requirements for vitamins and minerals (NASEM, 2016) for receiving cattle and supplied 24 mg/kg monensin sodium (DM basis).

[4]Formulated to meet or exceed NASEM requirements for vitamins and minerals (NASEM, 2016) for receiving cattle and supplied 37 mg/kg monensin sodium and 9 mg/kg tylosin phosphate on a DM basis.

[6]Analyzed and calculated by Servi-Tech Laboratories (Hastings, NE).

[7]$TDN = 4.898 + (89.796 \times NE_{Lact})$.

[8]ME = TDN × 0.01642 (NRC, 1988).

[9]NEm = (1.37 × ME) - (0.3042 × ME^2) + (0.051 × ME^3) - 0.508 (NRC, 1988).

[10]NEg = (1.42 × ME) - (0.3836 × ME^2) + (0.0593 × ME^3) - 0.7484 (NRC, 1988).

Table 4. Individual feed ingredient nutrient composition used throughout study

Item	SB[1]	WDGS[2]	SFC[3]	CS[4]	CSM[5]
n	26	26	6	6	6
Nutrient, % of DM[6]					
DM					
Mean	60.33	31.02	83.97	87.45	90.72
Minimum	56.60	29.00	80.40	86.10	89.50
Maximum	63.90	33.10	86.40	90.50	92.70
CV[7]	3.39	3.63	2.55	2.05	1.19
CP					
Mean	22.45	35.35	8.35	5.92	46.02
Minimum	21.60	33.60	7.50	4.70	44.20
Maximum	23.50	36.70	9.20	7.10	47.00
CV	2.13	2.53	8.79	16.33	2.10
Fat					
Mean	2.93	10.37	3.13	0.63	3.05
Minimum	2.30	9.20	2.70	0.20	2.70
Maximum	3.60	11.70	3.50	1.00	3.40
CV	10.91	5.45	8.72	49.60	9.45
ADF					
Mean	10.86	18.04	3.87	52.32	18.45
Minimum	8.10	11.20	3.10	47.40	16.00
Maximum	12.30	22.20	5.50	56.50	20.40
CV	8.29	11.70	22.47	6.61	8.14
NEm Mcal/kg					
Mean	1.96	1.79	2.10	0.75	1.79
Minimum	1.91	1.69	2.07	0.59	1.74
Maximum	2.00	1.96	2.11	0.97	1.85
CV	1.10	2.73	0.88	19.36	2.12
NEg Mcal/kg					
Mean	1.30	1.17	1.44	0.22	1.17
Minimum	1.28	1.08	1.39	0.07	1.12
Maximum	1.34	1.30	1.45	0.42	1.21
CV	1.17	3.39	1.85	63.15	2.67

[1]Sweet Bran (SB).

[2]Wet distillers grains with solubles (WDGS).

[3]Steam-flaked corn (SFC).

[4]Corn Stalks (CS).

[5]Cottonseed meal (CSM).

[6]Analyzed and calculated by Servi-Tech Laboratories (Hastings, NE).

[7]Coefficient of variation (CV).

Table 5. Total starch and starch availability of steam-flaked corn used throughout study

Item	SB[1]	WDGS[2]	SFC[3]	CS[4]	CSM[5]
n			27		
Total Starch					
Mean	-	-	78.93	-	-
Minimum	-	-	74.40	-	-
Maximum	-	-	83.40	-	-
CV	-	-	3.02	-	-
Starch Availability					
Mean	-	-	58.56	-	-
Minimum	-	-	44.00	-	-
Maximum	-	-	75.00	-	-
CV	-	-	11.90	-	-

[1]Sweet Bran (SB).
[2]Wet distillers grains with solubles (WDGS).
[3]Steam-flaked corn (SFC).
[4]Corn Stalks (CS).
[5]Cottonseed meal (CSM).
[6]Analyzed and calculated by Servi-Tech Laboratories (Hastings, NE).
[7]Coefficient of variation (CV).

Table 6. Effects of diets containing no fibrous corn-milling byproducts, wet distillers grain with solubles and/or Sweet Bran on finishing cattle performance

	Treatments[1]					
Items	CON	WDGS	SB	COMBO	SEM[2]	*P*-value
Unshrunk BW, kg						
Initial	373	374	373	373	15.54	0.85
Transition	417	418	418	417	16.07	0.94
Final	616[b]	630[a]	630[a]	626[a]	4.79	< 0.01
DMI, kg						
D0 to Transition	9.51	9.60	9.66	9.71	0.33	0.44
Transition to Final	9.02[b]	9.72[a]	9.75[a]	9.61[a]	0.16	< 0.01
D0 to Final	9.10[b]	9.72[a]	9.76[a]	9.64[a]	0.18	< 0.01
ADG, kg						
D0 to Transition	2.18	2.21	2.24	2.18	0.10	0.96
Transition to Final	1.46[b]	1.56[a]	1.56[a]	1.54[a]	0.03	< 0.01
D0 to Final	1.56[b]	1.65[a]	1.65[a]	1.62[a]	0.04	< 0.01
G:F, kg						
D0 to Transition	0.23	0.23	0.23	0.23	0.01	0.93
Transition to Final	0.16	0.16	0.16	0.16	0.002	0.87
D0 to Final	0.17	0.17	0.17	0.17	0.002	0.48
Carcass-Adjusted						
Final BW[3]	615[b]	630[a]	631[a]	626[a]	4.96	0.01
ADG[4]	1.52[b]	1.62[a]	1.63[a]	1.59[ab]	0.05	0.01
G:F[5]	0.16	0.17	0.17	0.17	0.003	0.25
Performance-Adjusted						
NEm, Mcal/kg	2.22	2.19	2.19	2.18	0.02	0.13
NEg, Mcal/kg	1.54	1.51	1.51	1.50	0.02	0.13
Ratio NEm, Mcal/kg[6]	1.00	1.01	1.02	1.00	0.01	0.25
Ratio NEg, Mcal/kg	1.00	1.02	1.01	1.00	0.01	0.32

[1]CON = control, no byproduct; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles.
[2]Standard error of the mean. Means within a row with different superscript letters differ, $P < 0.05$.
[3]Carcass-adjusted final BW = HCW/0.646.
[4]Carcass-adjusted ADG = Carcass adjusted final BW– Initial BW/DOF.
[5]Carcass-adjusted G:F = Carcass adjusted ADG/DMI.
[6]Net energy ratios were calculated by dividing the estimated energy concentration of the diet by the performance-adjusted energy values.

Table 7. Effects of no fibrous corn-milling byproducts, wet distillers grain with solubles, and/or Sweet Bran on finishing cattle carcass characteristics

	Treatments[1]					
Item	CON	WDGS	SB	COMBO	SEM[2]	*P*-value
HCW, kg	398[b]	407[a]	408[a]	404[ab]	3.42	0.04
Dressing, %	63.72	64.98	64.89	65.03	0.83	0.21
Marbling Score[3]	44.2	43.8	45.0	43.9	1.15	0.63
12th-rib fat, cm	1.40	1.50	1.43	1.41	0.06	0.41
LM area, cm^2	100.0	99.1	99.4	99.2	1.02	0.50
KPH, %	2.28	2.26	2.29	2.26	0.06	0.33
Yield Grade[4]	2.66	2.92	2.85	2.80	0.11	0.09
Quality Grade, %						
Select	28.99	34.43	24.25	28.99	6.05	0.46
Choice	45.77	39.94	51.37	49.82	5.50	0.35
Premium Choice	20.63	20.35	19.80	16.67	5.91	0.88
Choice or Greater	70.28	63.89	75.98	70.26	6.36	0.32
Liver Score						
Abscessed, %	20.45	14.82	12.57	11.16	4.24	0.27

[1]CON = control, no byproduct; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles.
[2]Standard error of the mean. Means within a row with different superscript letters differ, $P < 0.05$.
[3]Leading digit in marbling number indicates marbling score; 2=trace, 3=slight, 4=small, 5=modest, 6=moderate, 7=slightly abundant, 8=moderately abundant, 9=abundant. Following digits indicate degree of marbling within marbling score.
[4]Calculated using the USDA (2017) regression equation.

Table 8. Particle separation and physically effective NDF (peNDF) analysis of diets formulated with no fibrous corn-milling byproducts, wet distillers grain with solubles, and/or Sweet Bran

	Treatments[1]					
Item	CON	WDGS	SB	COMBO	SEM[2]	*P*-value
No. of Samples	25	25	25	25	-	-
NDF, % of DM[3]	14.46[c]	18.78[b]	18.82[b]	21.70[a]	0.28	< 0.01
Sieve Screen Size, mm	Retained / Screen, %					
19.0	0.408	0.554	0.687	0.546	0.08	0.10
8.0	41.21[a]	32.91[b]	34.51[b]	28.98[c]	1.39	< 0.01
4.0	22.31[a]	19.39[b]	23.05[a]	22.08[a]	0.51	< 0.01
1.18	19.02[c]	25.46[b]	26.29[b]	30.75[a]	0.52	< 0.01
Particles > 4mm	63.92[a]	52.86[c]	58.25[b]	51.60[c]	1.04	< 0.01
Est. peNDF[4], % of DM	9.22[c]	9.93[b]	10.95[a]	11.19[a]	0.23	< 0.01

[1]CON = control, no byproduct; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles.
[2]Standard error of the mean. Means within a row with different superscript letters differ, $P < 0.05$.
[3]Analyzed and calculated by Servi-Tech Laboratories (Hastings, NE).
[4]peNDF was calculated by multiplying the percentage of weight (DM basis) from the top 3 sieves by the NDF content (DM basis) of the diet and expressed as a percentage (Gentry et al., 2016).

Table 9. Ruminal pH and rumination minutes in proportion to DM, NDF and peNDF intake of finishing beef cattle consuming diets formulated with no fibrous corn-milling byproducts, wet distillers grain with solubles, and/or Sweet Bran

	Treatment[1]					*P*-value		
Item	CON	WDGS	SB	COMBO	SEM[2]	Treatment	Day	TRT × Day
Daily ruminal pH	5.47[c]	5.63[b]	5.69[ab]	5.78[a]	0.05	< 0.01	< 0.01	0.40
Rumination, min/d	410	436	460	442	20.41	0.39	< 0.01	< 0.01
Rumination, min/kg								
DM	46.77	45.50	48.41	46.83	2.24	0.81	< 0.01	< 0.01
NDF	323[a]	242[b]	257[b]	216[b]	12.32	< 0.01	< 0.01	< 0.01
peNDF	507[a]	458[ab]	442[b]	418[b]	21.71	0.02	< 0.01	< 0.01

[1]CON = control, no byproduct; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles.

[2]Standard error of the mean. Means within a row with different superscript letters differ, $P < 0.05$.

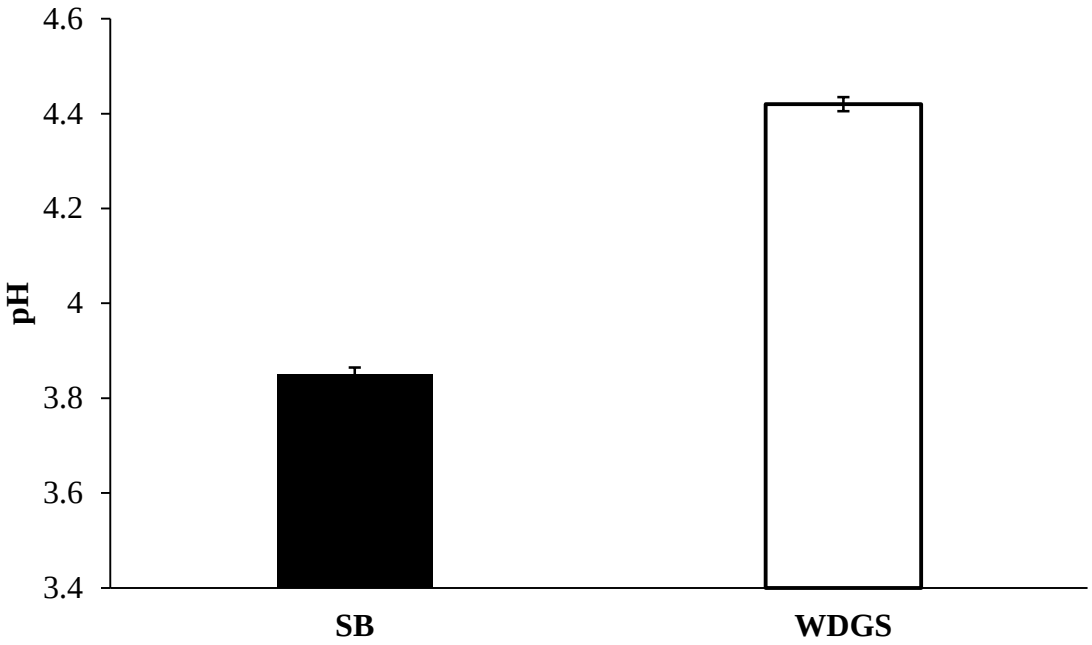

Figure 1. Individual fibrous corn-milling byproduct ingredient pH measured by mixing weekly-composited samples in de-ionized water before measuring with a pH meter (VWR International, Radnor, PA; FAO, 2011). Sweet Bran (SB); Wet distillers grains with solubles (WDGS). Effect of ingredient, $P < 0.01$.

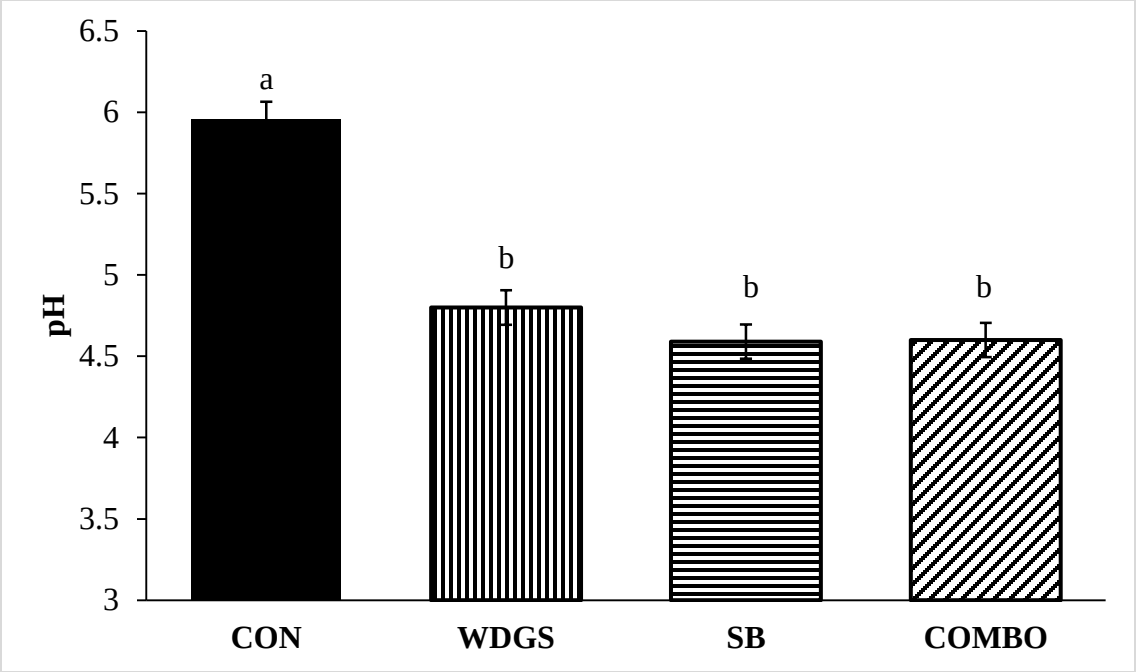

Figure 2. Treatment diet pH measured by mixing composited samples in de-ionized water before measuring with a pH meter (VWR International, Radnor, PA; FAO, 2011). CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Effect of diet, $P < 0.01$.

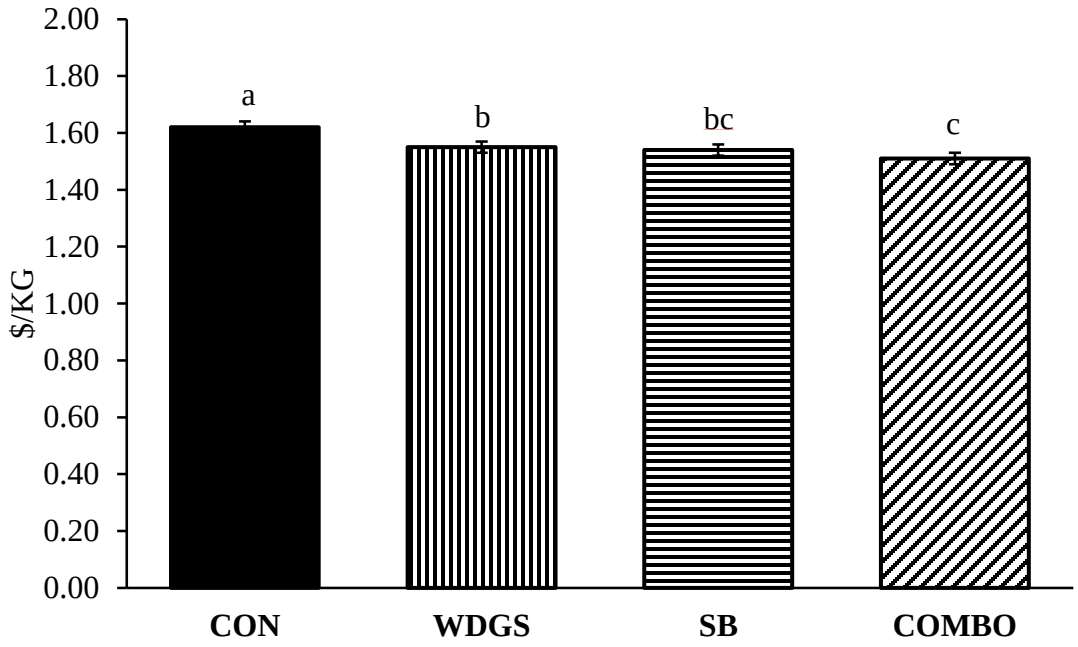

Figure 3. Cost of gain for each dietary treatment including CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Effect of diet, $P < 0.01$.

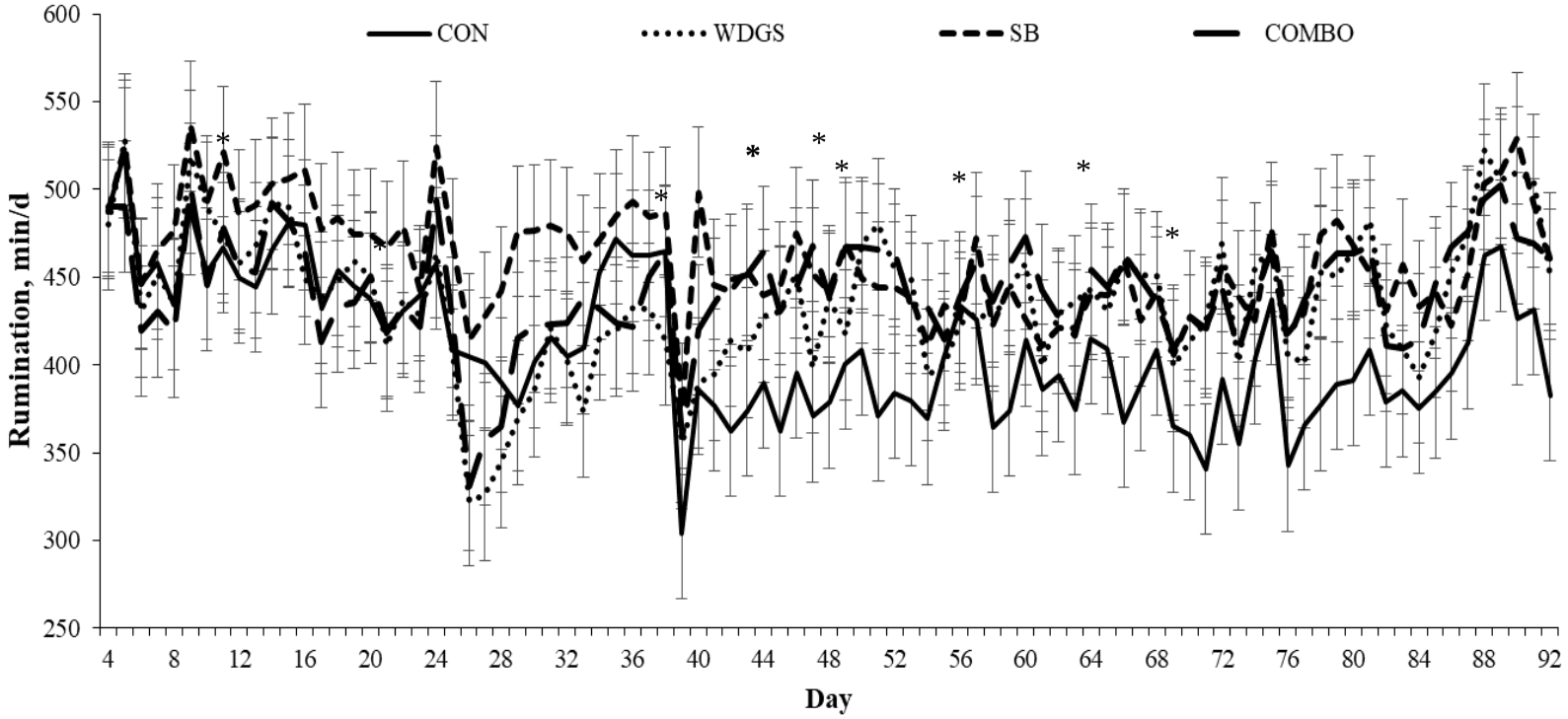

Figure 4. Daily rumination of finishing steers fed CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive a 3-axis accelerometer tag (Allflex Livestock Intelligence, Madison, WI) to quantify rumination time which was continuously recorded and reported as the average of rumination time within a 2 h period. Effect of diet, $P = 0.39$; day, $P < 0.01$; diet × day, $P < 0.01$.

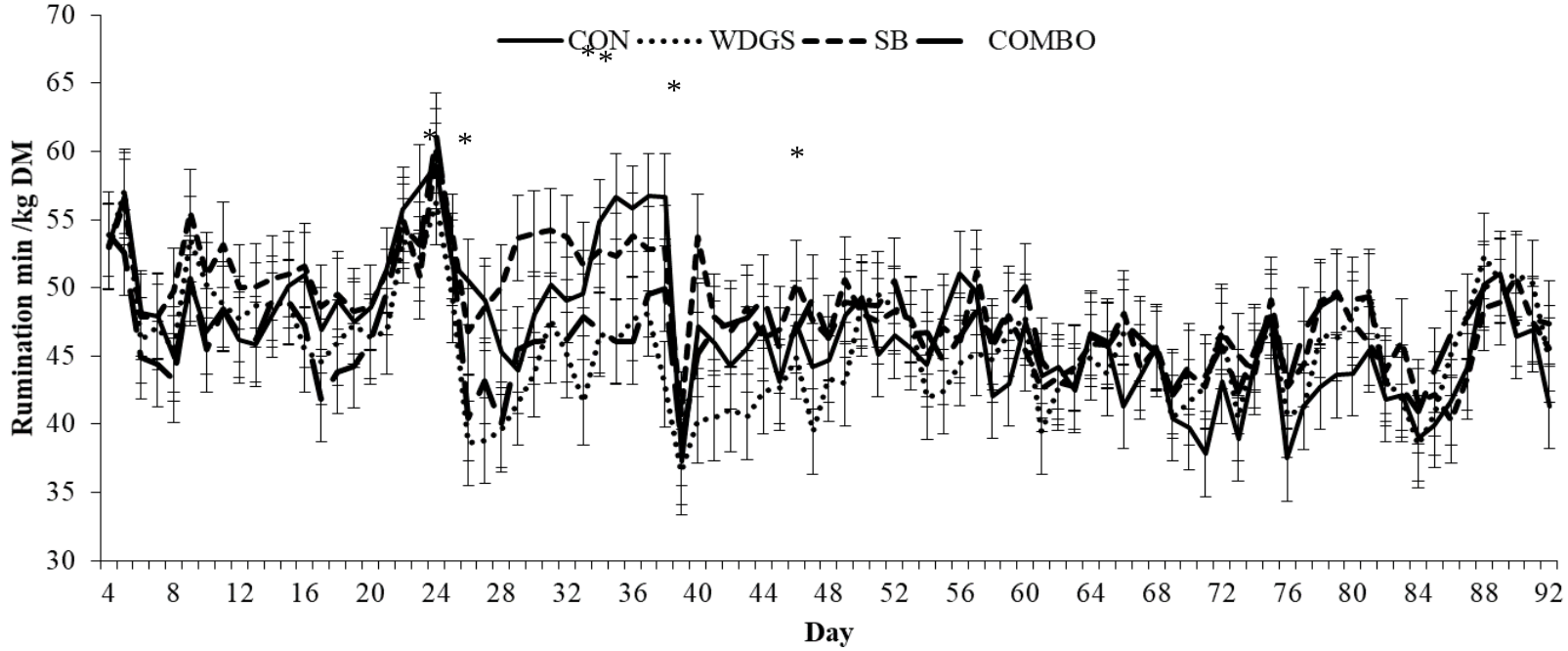

Figure 5. Daily rumination per kg of DM consumed by finishing steers fed CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive a 3-axis accelerometer tag (Allflex Livestock Intelligence, Madison, WI) to quantify rumination time and was continuously recorded and reported as the average of rumination time within a 2 h period. Effect of diet, $P = 0.81$; time, $P < 0.01$; diet × time, $P < 0.01$.

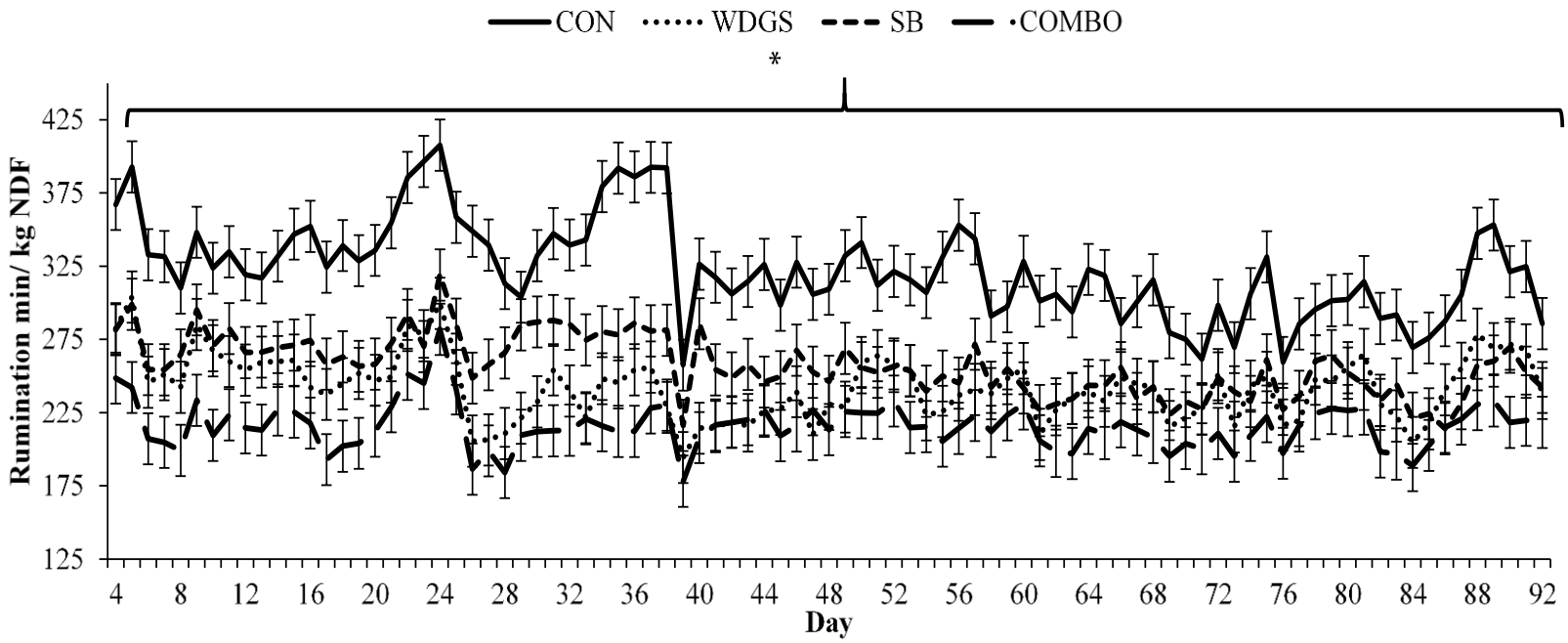

Figure 6. Daily rumination per kg of NDF intake of finishing steers fed CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive a 3-axis accelerometer tag (Allflex Livestock Intelligence, Madison, WI) to quantify rumination time and was continuously recorded and reported as the average of rumination time within a 2 h period. Effect of diet, $P < 0.01$; time, $P < 0.01$; diet × time, $P < 0.01$.

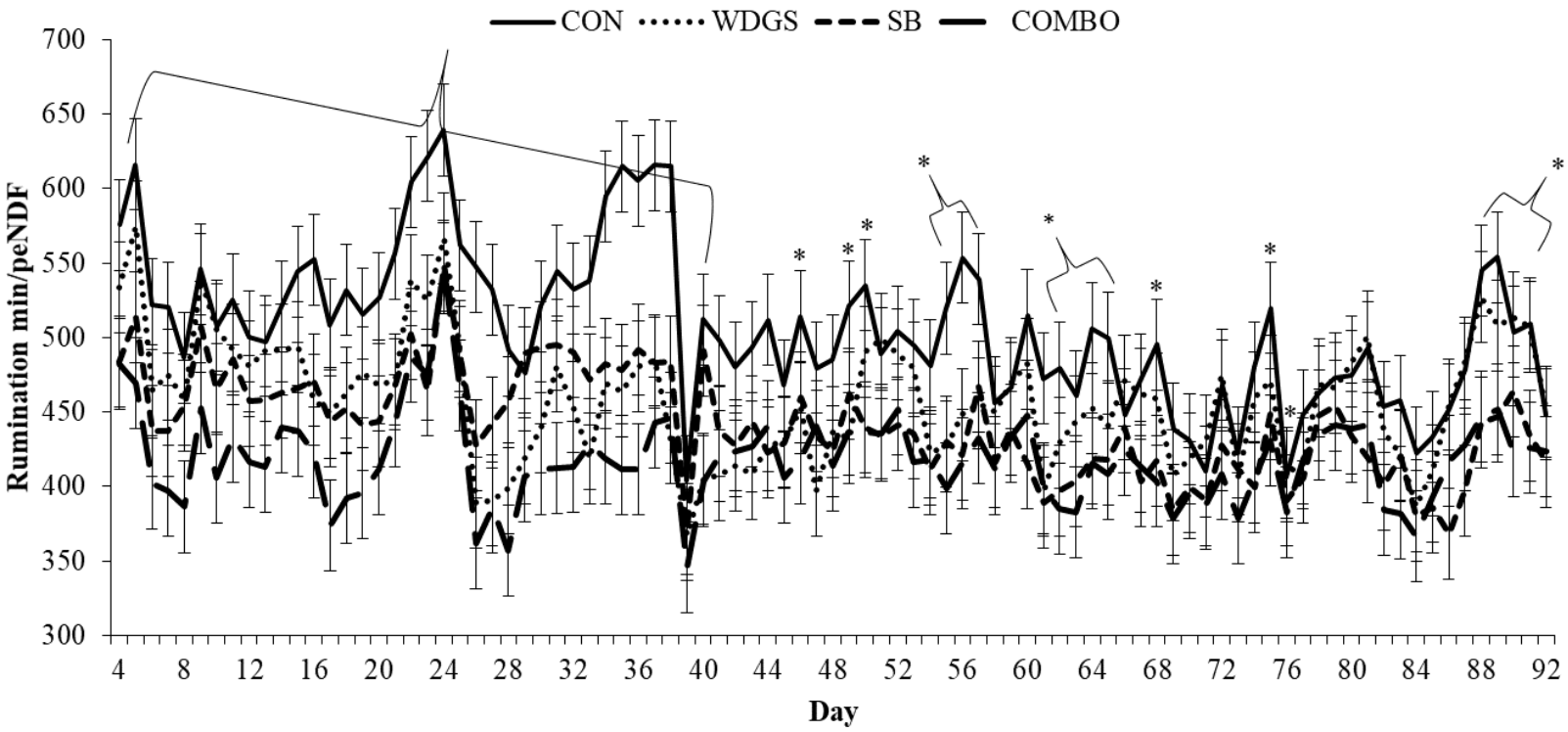

Figure 7. Daily rumination per kg of peNDF intake of finishing steers fed CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive a 3-axis accelerometer tag (Allflex Livestock Intelligence, Madison, WI) to quantify rumination time and was continuously recorded and reported as the average of rumination time within a 2 h period. Effect of diet, $P < 0.02$; time, $P < 0.01$; diet × time, $P < 0.01$.

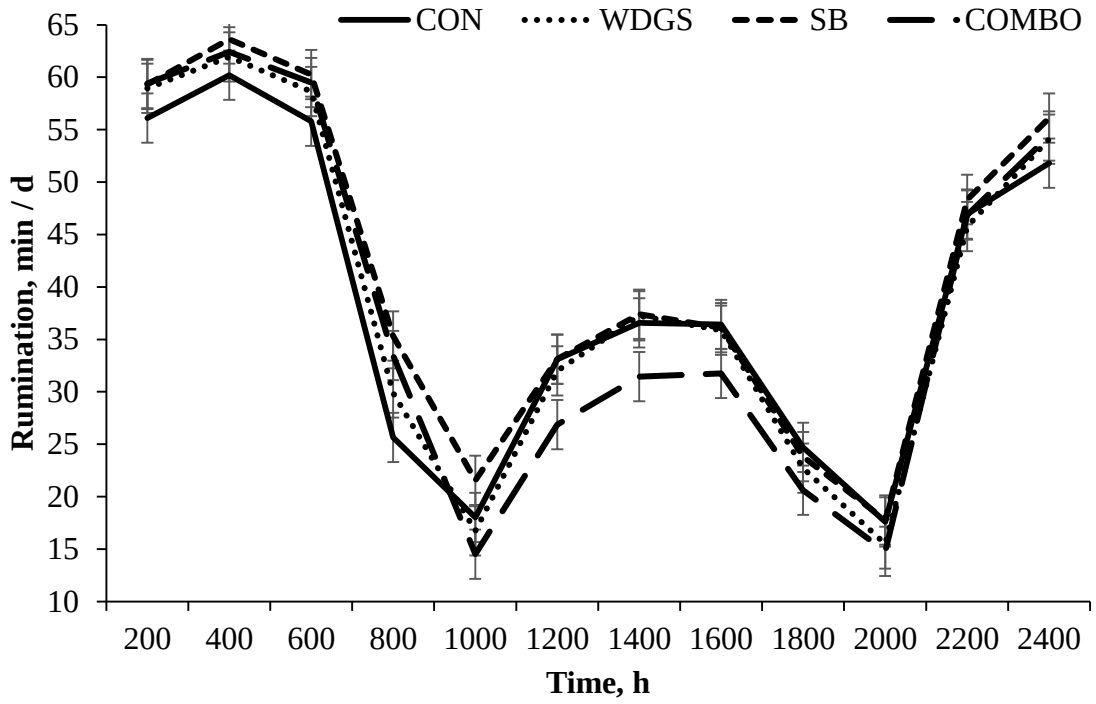

Figure 8. Circadian hourly rumination during the dietary transition period of finishing steers fed CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive a 3-axis accelerometer tag (Allflex Livestock Intelligence, Madison, WI) to quantify rumination time and was continuously recorded and reported as the average of rumination time within a 2 h period. Effect of diet, $P = 0.42$; time, $P < 0.01$; diet × time, $P = 0.61$.

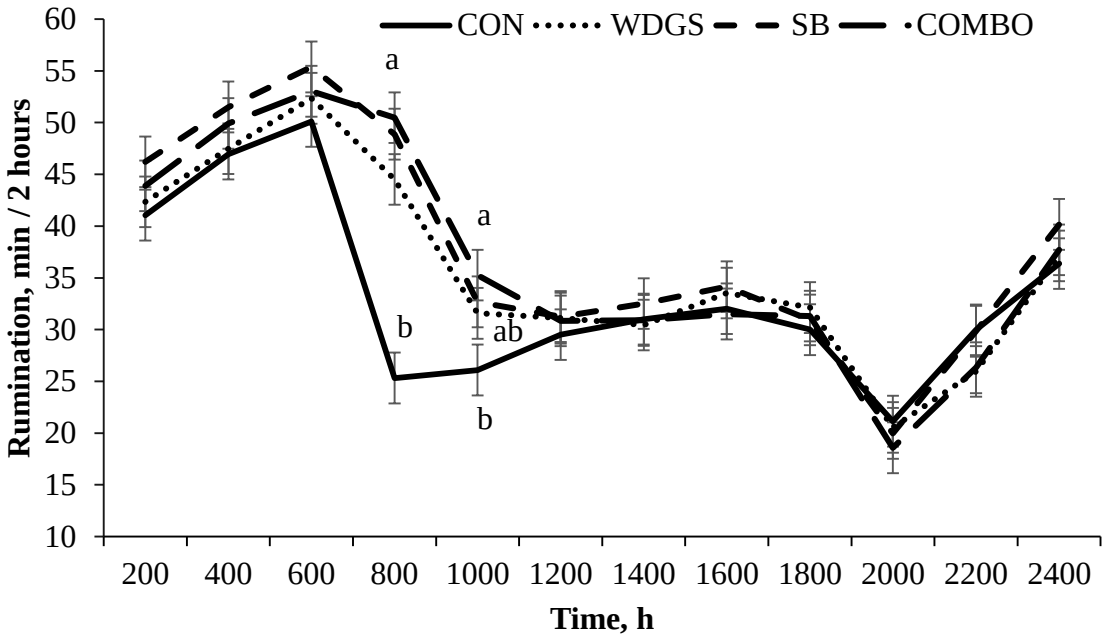

Figure 9. Circadian hourly rumination after the dietary transition period of finishing steers fed CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive a 3-axis accelerometer tag (Allflex Livestock Intelligence, Madison, WI) to quantify rumination time and was continuously recorded and reported as the average of rumination time within a 2 h period. Effect of diet, $P = 0.37$; time, $P < 0.01$; diet × time, $P < 0.01$.

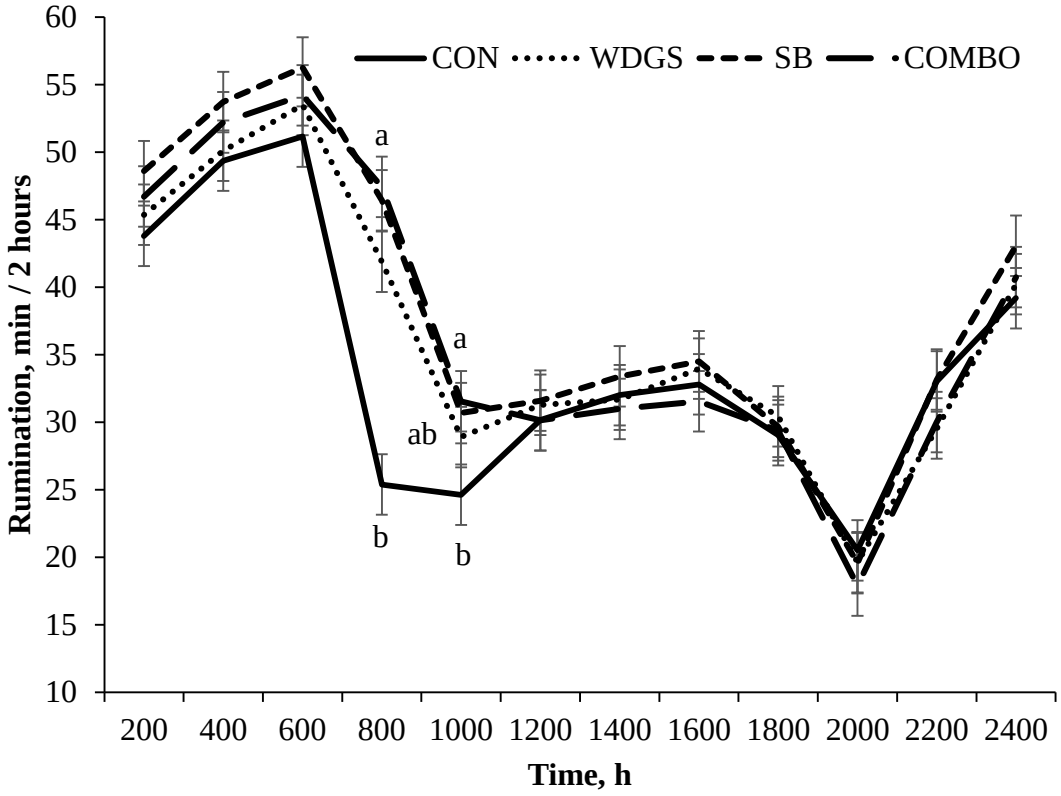

Figure 10. Circadian hourly rumination of finishing steers fed CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive a 3-axis accelerometer tag (Allflex Livestock Intelligence, Madison, WI) to quantify rumination time and was continuously recorded and reported as the average of rumination time within a 2 h period. Effect of diet, $P = 0.37$; time, $P < 0.01$; diet × time, $P < 0.01$.

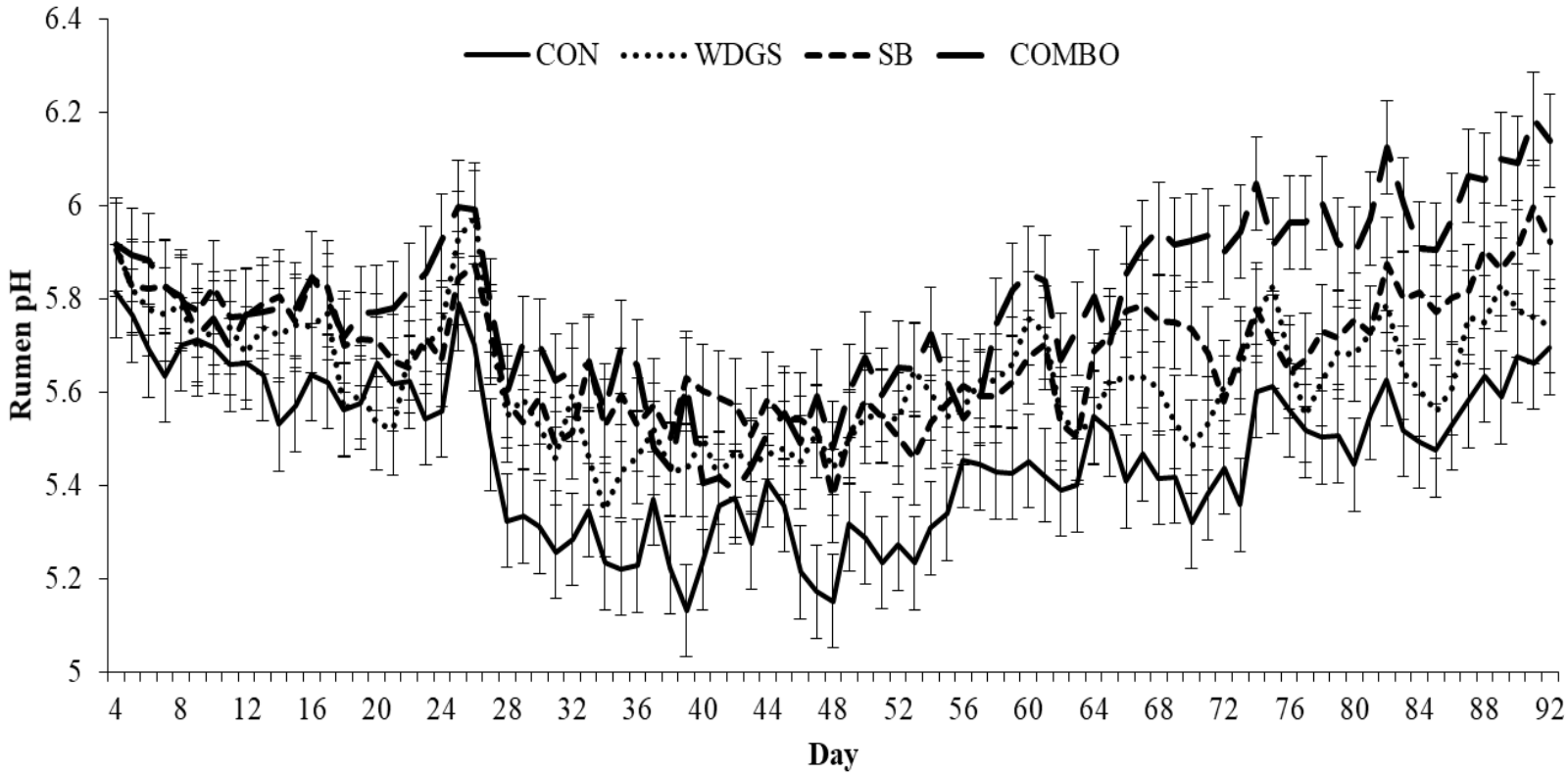

Figure 11. Daily ruminal pH of finishing steers fed CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive both an indwelling ruminal pH bolus (Well Cow Limited, Roslin, UK) and ruminal pH data were automatically logged in 15 min time intervals. Effect of diet, $P < 0.01$; day, $P < 0.01$; diet × day, $P = 0.40$.

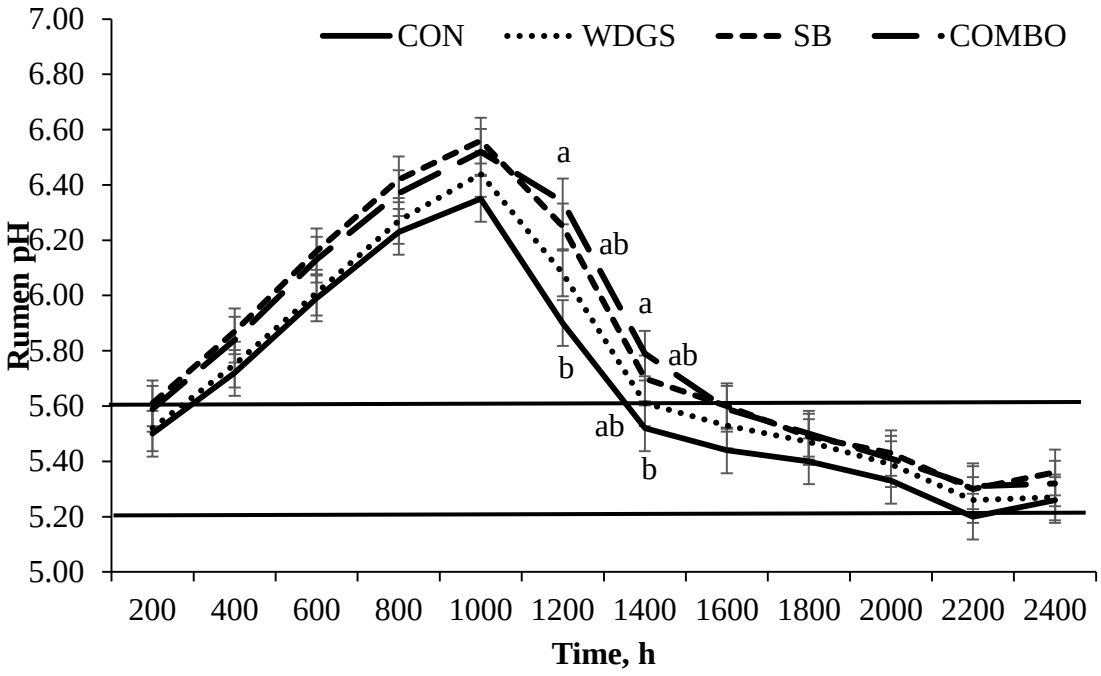

Figure 12. Circadian hourly ruminal pH during the dietary transition period of finishing steers fed CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive both an indwelling ruminal pH bolus (Well Cow Limited, Roslin, UK) and ruminal pH data were automatically logged in 15 min time intervals. Effect of diet, $P = 0.26$; time, $P < 0.01$; diet × time, $P = 0.02$.

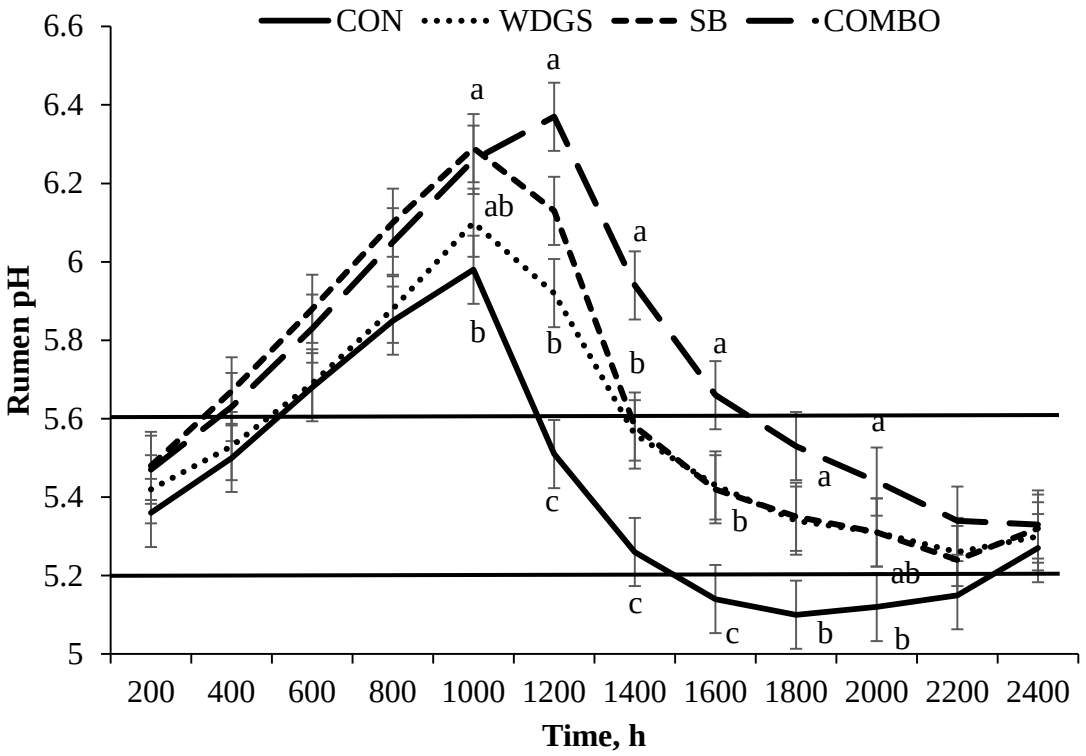

Figure 13. Circadian hourly ruminal pH after the dietary transition period of finishing steers fed CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive both an indwelling ruminal pH bolus (Well Cow Limited, Roslin, UK) and ruminal pH data were automatically logged in 15 min time intervals. Effect of diet, $P = 0.01$; time, $P < 0.01$; diet × time, $P < 0.01$.

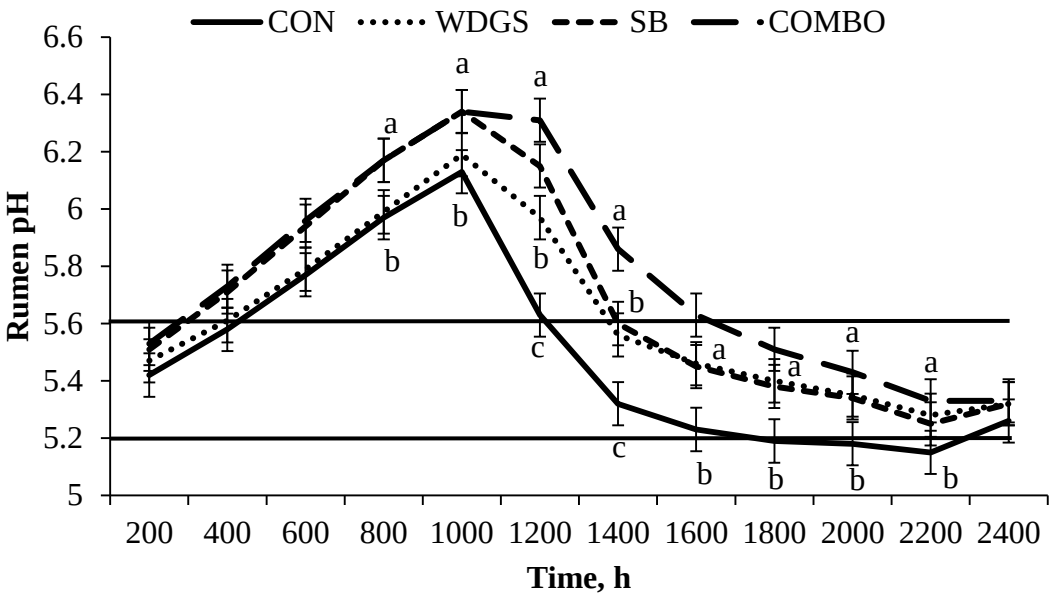

Figure 14. Overall circadian hourly ruminal pH of finishing steers fed CON = control, no fibrous corn-milling byproducts; WDGS = 20% wet distillers grains with solubles; SB = 20% Sweet Bran; COMBO = 20% Sweet Bran and 10% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive both an indwelling ruminal pH bolus (Well Cow Limited, Roslin, UK) and ruminal pH data were automatically logged in 15 min time intervals. Effect of diet, $P = 0.01$; time, $P < 0.01$; diet × time, $P < 0.01$.