DIETARY STARCH DILUTION STRATEGIES TO IMPROVE RUMEN HEALTH AND PERFORMANCE IN FEEDLOT CATTLE

by

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ABSTRACT

The objectives of this study were to evaluate the effects of starch dilution with different sources of dietary fiber from terminal implant to slaughter on feedlot cattle performance, carcass characteristics, and rumen buffering characteristics. Steers (n = 416; 372 ± 2.67 kg) were allocated to 48 pens in a randomized complete block design. Pens of cattle (n = 12 per treatment) were assigned to 1 of 4 treatments consisting of steam-flaked corn-based diets containing: 1) **CON**; 7.50 % corn stalks on a DM basis fed for the entire feeding period, 2) **CS;** 14.75% corn stalks on a DM basis fed from terminal implant to slaughter, 3) **WD**; 9.50% wet distillers grains with solubles, and 7.50% corn stalks on a DM basis fed from terminal implant to slaughter, and 4) **NR**; 19.00% wet distillers grains with solubles, and 0.0% corn stalks on a DM basis fed from terminal implant to slaughter. Six days before administration of the terminal implant, steers were transitioned to their treatment diets using a two-ration system, whereas CON consumed the same diet throughout the entire feeding period. Within each pen, 2 steers were randomly selected to receive an indwelling ruminal pH bolus to quantify rumen pH and a 3-axis accelerometer tag to assess rumination time. Diet samples were collected weekly to determine particle size, NDF concentration, and physically effective fiber (peNDF). At slaughter, rumens were evaluated for the presence of scarring and lesions. Performance (BW, DMI, ADG, G:F) was not different ($P \geq 0.34$) from initial to transition. Dry matter intake and metabolizable energy intake from transition to final were greatest for cattle consuming CS, intermediate for WD and CON, and least for NR ($P < 0.01$). Final BW and ADG did

not differ among treatments from transition to final ($P \geq 0.19$); however, G:F was greatest for NR, intermediate for WD, and least for CS and CON ($P = 0.10$). There was no difference ($P \geq 0.24$) in hot carcass weight, dressing percentage, marbling score, quality grade, yield grade, and percentage KPH fat among treatments. Steers consuming CS had greater ($P = 0.08$) 12^{th} rib fat thickness. The proportion of abscessed livers did not differ ($P = 0.26$) among treatments. The peNDF was greatest for CS, intermediate for WD and CON, and least for NR ($P < 0.01$). Particles > 4.0 mm were greatest for CON and CS, intermediate for WD, and least for NR ($P < 0.01$). A treatment × day interaction ($P < 0.01$) was observed for daily rumination minutes and rumination per kg of DMI; rumination was greater for CS, intermediate for WD and CON, and least for NR early in the finishing period and greater for CS than NR towards the end of the finishing period. Similarly, a treatment × hour effect ($P < 0.01$) was observed for hourly rumination; cattle consuming CS had greater rumination than NR at 0200, 0400, 0600, 1200, 1400, 2000, 2200 and 2400 h. There was also a treatment × day interaction ($P < 0.01$) for rumen pH, but the diet appeared to have minimal effects on pH throughout the entire feeding period. A treatment × hour effect ($P < 0.01$) was observed for hourly pH; cattle consuming CON had greater rumen pH than WD and NR at 0400, 0600, and 800 h, but had minimal effects throughout the remainder of the 24 h period. Rumen scores of cattle consuming CON had a greater ($P = 0.09$) percentage of rumen score 3, but there were no other differences among dietary treatments ($P > 0.31$)The results of this study indicate that increasing the proportion of corn stalks in the diet post-terminal implant administration increases DMI, dietary peNDF, and rumination time. However, ruminal pH was minimally impacted by decreased starch and greater fiber provided from either corn stalks or WDGS and suggests that roughage can be replaced with fibrous corn milling byproducts without negatively impacting rumen health.

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Introduction

Feedlot cattle are fed high concentrate diets containing readily available starch to maximize performance and minimize feed cost per unit of energy (Brown et al., 2006; Samuelson et al., 2016). These diets are rapidly fermentable and can result in excess production of volatile fatty acids (VFA's) which alter the rumen environment and increase the risk for digestive disorders, such as ruminal acidosis. Ruminal acidosis can reduce growth performance and predispose cattle to liver abscesses, which can increase trim loss and reduce carcass and carcass values.

Roughage makes up a relatively small proportion of finishing cattle diets but is considered necessary to stimulate rumination and maintain ruminal health and integrity. However, drought conditions throughout the western United States have decreased the supply of forage to beef producers and geographical proximity to forage producing regions can be a limiting factor for some cattle feeding operations. Because of their bulk density, roughage sources can also place additional wear and tear on feed manufacturing equipment and negatively impact feeding logistics. As a result, there is interest in replacing traditional roughage sources in the diet with alternative sources of fiber such as corn milling byproducts. Wet corn gluten feed (WCGF), Sweet Bran, and wet distillers grains with solubles (WDGS) are corn milling byproducts commonly used as a source of energy and protein in feedlot diets.

Physically effective neutral detergent fiber (peNDF) is described as a combination of both the neutral detergent fiber (NDF) concentration and particle size of a feedstuff that potentiates rumination (Mertens, 1997). Because of the high NDF content of corn milling byproducts, these feedstuffs have a relatively high peNDF. However, corn milling byproducts have a small particle size, and Mertens (1997) assumed that any feed particles < 1.18 mm are readily passed through the reticulo-omasal orifice without re-mastication or ruminal fermentation. Alternatively, particles greater than 4.0-mm have been found in the duodenal digesta more recently (Heinrichs et al., 2013). Regardless of particle size, these feedstuffs have the potential to supply additional fiber and dilute the starch concentration of the diet. This literature review will discuss starch in feedlot diets, the defining characteristics of fiber and value of physically effective fiber, ruminal health, and rumination, as well interactions between roughages and corn milling byproducts in feedlot diets.

Ruminant Digestion

In ruminant animals, the rumen plays a vital role in feed fermentation and nutrient digestion. Because of the microbial population present in the rumen, ruminants have a high capacity to digest and absorb nutrients from lowly digestible forages because of microbial fermentation of cellulose and other indigestible compounds (Hungate, 1966; Benton et al., 2010). When feed enters the rumen, microbes attach to feed particles and degrade the nutrients present in feeds into smaller, less complex units that are more easily absorbed by protozoa and bacteria (Hungate, 1966). After digestion and absorption, ruminal microbes can metabolize the nutrients present in feeds and use the resulting end-products for growth and reproduction. In feedlot cattle, microbial digestion and fermentation of carbohydrates is key for producing usable energy. Microbial fermentation of carbohydrates yields energy in the form of adenosine triphosphate (ATP) and produces short-chain fatty acids known as VFA's (Church, 1988). The VFA's produced are then used as a source of energy for the animal, whereas the ATP generated is used as the primary source of energy for growth and maintenance of ruminal bacteria. Approximately 75 to 85% of feed energy is converted to VFA, whereas the remainder is lost as heat and CH_4 (Sutton, 1979).

The three primary VFA's are acetate, propionate, and butyrate. These VFA's are absorbed across the rumen wall and travel through a concentration gradient to be used in target tissues (Church, 1988). Acetate reaches the liver via portal circulation, and most is passed into peripheral circulation and oxidized via the tricarboxylic acid cycle. Propionate reaches the liver via portal circulation and is either oxidized or used in gluconeogenesis. Butyrate is converted to ketones and low levels of butyrate circulate in the blood (Church, 1988).

Gut Morphology

In feedlot cattle, the consumption of highly fermentable diets and concomitant increase in acid production and reduction in ruminal pH challenges the regulation of homeostasis of the ruminal environment, including the epithelia (Penner et al., 2011). The ruminal and gastrointestinal epithelium of cattle must protect the host from potentially pathogenic contents of the luminal environment, while also facilitating absorption of nutrients (Steele et al., 2016). Because the gastrointestinal tract (GIT) is an important component of animal metabolism, local adaptations in the gut will also play a systemic role in a beef animal (Steele et al., 2016). Adaptation of the epithelial tissue in the GIT involves morphological adaptations and changes in individual cell function (Gabel and Aschenbach, 2007) that can be disrupted in a low pH environment.

An important player in the function of the rumen are the papillae that protrude from the ruminal epithelium, which increase absorptive surface area for VFA uptake (Steele et al., 2016). Development of the rumen and rumen papillae begins with solid feed intake in young calves. Growth of rumen papillae is evaluated by measuring the height and width of papillae as an estimate of epithelium growth (Steele et al., 2014). However, increased height and width are not always equivalent to increased absorptive capacity, because density of the papillae also plays a role in absorptive function (Steele et al., 2014). Volatile fatty acids, such as acetate, butyrate, and propionate, are considered luminal growth factors and increased production in highly fermentable feedlot diets alters GIT proliferation. Of those three acids, butyrate is reported to be the most stimulatory for epithelial proliferation (Penner et al., 2011).

Studies evaluating the response of the epithelial tissue to dietary changes have been conducted in calves during the period of transition from pre-ruminants to functional ruminants, and in late gestation dairy cattle; however, there is limited research in feedlot cattle transitioned from backgrounding to finishing diets (Penner et al., 2011). Gut health is a loosely defined term, especially in feedlot cattle; further research is needed to identify what feed ingredients and strategies are necessary to maintain it. Dietary composition, nutrient digestibility, feeding management and individual animal eating behavior can heavily influence the microbial population as well as the distribution, size, and overall health of rumen papillae (Church, 1988). In feedlot cattle consuming diets containing high proportions of processed grains, greater concentrations of readily degradable starch increase the risk for metabolic disorders, which can damage the ruminal epithelium, decrease absorptive capacity, and impact gut motility (Owens et al., 1998).

Rumen Health and Acidosis

Metabolic disorders account for 10.4% of feedlot mortalities, and among them, acidosis is the most common in beef operations in the U.S. (USDA, 2011). Ruminal acidosis is a common digestive disorder in feedlot cattle that erodes the ruminal epithelium and decreases absorptive capacity (Castillo-Lopez, 2014), which negatively impacts intake, feed efficiency, and growth performance (Krehbiel et al., 1995). Maintenance of ruminal pH within the physiological range of 5.8 to 6.5 is critical for upkeep of a healthy rumen microbial population and integrity of the rumen wall and associated papillae (Nagaraja et al., 2007). In contrast, ruminal acidosis is characterized by continual low pH and can be classified as acute or subacute. For example, a pH range of 5.2 to 5.6 is considered subacute acidosis, and a pH below 5.2 is classified as acute acidosis (Owens et al., 1998). Acidosis begins with an abrupt increase in consumption of readily fermentable carbohydrates and rapid fermentation to VFA's. Cattle consuming high concentrate diets have access to more fermentable carbohydrates than those consuming forage-based diets. Furthermore, consumption of rapidly fermentable carbohydrates shifts the microbial population in favor of amylolytic bacteria species (Goad et al., 1998; Tajima et al., 2001), which further facilitates production of VFA's (Schwartzkopf-Genswein et al., 2003). With a rapid increase in carbohydrate supply to the rumen, VFA's accumulate because their concentration is beyond the absorptive capacity of the rumen (Schwartzkopf-Genswein et al., 2003). In addition to the dietary concentration of readily fermentable carbohydrates, irregular consumption behavior that alters the supply of carbohydrates to the rumen may also facilitate acidosis (Schwartzkopf-Genswein et al., 2003).

The greatest risk for acidosis in feedlot cattle likely occurs during the adaptation period (Goad et al., 1998) from the rapid introduction of starch in the diet and at the end of the finishing period (Castillo-Lopez et al., 2014). At the end of the finishing period cattle are at peak dry matter intake (DMI) and prone to varying intake patterns as days on feed increase and may struggle to remove VFA's at the same rate they are produced (Castillo-Lopez et al., 2014). Management practices used to reduce variability of intake include programmed feeding, multiple daily feed deliveries, and consistent feeding time. However, their effectiveness is based on a pen average and does not account for individual animal variation (Schwartzkopf-Genswein et al., 2003). In the study by Schwartzkopf-Genswein et al. (2003), the authors concluded that cattle consuming high concentrate diets can adjust to inconsistencies in feed delivery and may be able to regulate their intake patterns so that variation in feed delivery is less impactful. This suggests that perhaps intake variation may have less of an impact on ruminal acidosis than the concentration of fermentable starch in feedlot diets, but additional research is needed to validate this hypothesis.

Liver Abscesses

In addition to the loss in performance associated with ruminal acidosis, acidosis has also been linked to secondary disorders, such as liver abscesses. The prevalence of liver abscesses varies greatly based on region, diet, and breed type; however, the prevalence of total liver abscesses in the U.S. feedlot industry ranges from 10 to 20% (Reinhardt and Hubbert, 2015). Liver abscesses pose an economic threat to the beef industry, reducing the value of a beef carcass by $38 per animal (Brown and Lawrence, 2010). Given current economic conditions, the reduction in carcass value and live performance is even greater today. Liver abscesses have also been associated with reduced carcass fatness, as cattle with liver abnormalities had less subcutaneous fat at the 12th rib and lower marbling scores (Brown and Lawrence, 2010). Davis et al. (2007) and Brown and Lawrence (2010) reported that mild and moderate liver abscesses had no or limited effects on animal performance, but severe liver abscesses could decrease average daily gain (ADG). In addition to ADG, DMI, body weight (BW) gain, and hot carcass weight (HCW) are reduced in cattle with severe liver abscesses (Brink et al., 1990).

The etiology of liver abscess formation is poorly understood, but it involves infection of the liver with *Fusobacterium necrophorum* and potentially other bacteria species. *Fusobacterium necrophorum* is a gram-negative, rod-shaped, non-spore forming, anaerobic bacteria that resides in the rumen and the environment (Tan et al., 1996). In the rumen these bacteria pose no threat to the host; however, hepatic infection with *Fusobacterium necrophorum* leads to liver abscesses (Emery et al., 1985). The *Fusobacterium necrophorum* population is increased roughly tenfold when cattle are adapted from a roughage to a concentrate diet (Tan et al., 1994).

Rumenitis, a result of acidosis, is believed to be the predisposing factor for liver abscesses, as a correlation was reported between ruminal ulcers and liver abscesses by Smith (1944), Jensen et al. (1954), and Rezac et al. (2014). In contrast, no correlation between rumen health and liver abscess prevalence was reported by Weiser et al. (1996). The decrease in ruminal pH, associated with excessive acid load from acidosis, weakens the ruminal epithelium and causes ruminal ulcers. Bacteria can then enter the portal blood stream via rumenitis-caused lesions and travel to the liver (Nagaraja and Chengappa, 1998). In the liver, micro abscesses are formed from an embolus of *Fusobacterium necrophorum* in the sinusoid, which eventually leads to coagulative necrosis within adjacent hepatocytes (Nagaraja et al., 1996b). A true abscess is formed when those lesions turn into encapsulated pus-filled pockets. These abscesses contain necrotic leukocytes and degenerating hepatocytes. They also contain a layer of macrophages around their necrotic center. Between the pus-filled capsule and the cellular layers of liver tissue, there is a progressive loss of cellularity, and an abscess near the surface often causes further inflammation (Nagaraja et al., 1996a). Inflammation leads to adhesion by fibrin collagen to the peritoneum and other surrounding viscera. In some cases, these abscesses can heal and become scars that have been remodeled by the liver. This pathology necessitates the need to maintain a healthy rumen in cattle consuming high concentrate diets to avoid the negative economic and performance implications from liver abscesses. Therefore, maintaining the balance between processed grains and roughage concentrations to facilitate rumen health is an important consideration for feedlot cattle diets.

Laminitis

Laminitis, more commonly referred to as founder, is characterized by the inflammation of the lamina surrounding the hoof bone. Laminitis has been linked to acidosis that occurs as a result of cattle consuming high concentrate diets and this progression has been associated with several systemic phenomena (Nocek et al., 1997). The link between acidosis and laminitis is believed to be associated with ischemia in the hoof of the animal. The laminitis cascade is initiated by a reduction in ruminal and even systemic pH from the consumption of highly fermentable diets. The impact of acidosis on ruminal osmolarity, hemoconcentration, and vascular deconstruction ultimately results in irreversible laminitis (Nocek et al., 1997). The development of laminitis can be segregated into four phases. The first phase begins with a reduction in systemic pH which activates a vaso-active mechanism that increases digital pulse and blood flow. The initial metabolic insult can also result in the release of endotoxins and histamine, which furthers vascular constriction and increases blood pressure. The increase in blood pressure causes damage to vessel walls which then release serum, causing edema and expansion of the corium of the hoof. Edema initiates phase two, where ischemia develops and causes hypoxia. Fewer nutrients and oxygen reach the epidermal cells, and this cycle repeats if metabolic insult continues to occur (Nocek et al., 1997). Mechanical damage to the hoof caused by the second phase initiates the third phase where the epidermis of the hoof breaks down and ultimate results in corium degeneration and breakdown of the laminar region. Finally, in the fourth phase separation of the laminar layer of the hoof tissue causes the bones to shift positions. Compression from the bone shifts inflicts damage to the soft tissues of the hoof and further enhances edema, thrombosis, and ischemia in what is now a necrotic area of the hoof (Nocek et al., 1997). Histamine has also been considered a responsible agent (Brent et al., 1976) because elevated serum histamine has been reported during acute laminitis of cattle on high concentrate diets (Maclean, 1970).

However, it is difficult to differentiate if high rumen histamine concentrations are related or coincidental and this etiology needs further research. Acidosis and laminitis appear to be related; however, the biochemical relationship is unclear and not all laminitis may be related to acidosis (Brent et al., 1976).

Dietary Starch from Processed Grains in Feedlot Diets

Starch is a non-structural glucose storage polysaccharide found in the endosperm of grains (Wolin, 1979). In beef cattle, most starch fermentation and digestion occur in the rumen, but at high levels of intake, small amounts of starch may leave the rumen undegraded (Church, 1998). As reported in a meta-analysis, increasing ruminal fermentation of starch maximized microbial protein synthesis, but was less energetically efficient than enzymatic digestion in the small intestine, and digestion in the large intestine is less efficient than both (Huntington et al., 2006). Greater starch availability in the small intestine increases total tract digestibility, energy utilization, and feed efficiency (Owens et al., 1986). However, there are several factors that limit the extent of starch digestion in the small intestine, including pre-digestion of starch in the rumen. Owens and Zinn (2005) reported that post-ruminal starch digestion was maximized in diets low in NDF and rich in nitrogen.

The most common source of starch in feedlot diets is processed grains. Digestibility of starch from whole grains is limited because of the protein matrix surrounding starch granules (Zinn et al., 2002). The primary goal of grain processing is to maximize ruminal starch availability and microbial fermentation to improve animal performance (Owens et al., 1997). This involves disrupting the protein matrix and granular structure of the starch (Church 1988). Processed grains can have varying rates of starch digestibility based on the processing method, grain type, moisture level, particle size, or length of storage (Stock et al., 2008). Steam-flaking is a common processing method used in the southern plains that increases the net energy for gain of corn by 18% based on improved feedlot cattle performance (Zinn et al., 2002). Starch availability recommendations vary by grain type, but for steam-flaked corn (SFC) availability is recommended to be 59.8% (Samuelson et al., 2016). Although increased digestibility of processed grains is beneficial to feedlot cattle performance, rapid fermentation of highly available starch can potentially lead to rumen dysfunction.

Starch Dilution and Impacts on Rumen Health

Feeding roughage is beneficial to rumen health and has been a common practice in cattle feeding for decades. Increasing the dietary roughage concentration stimulates chewing and saliva production, which provides ruminal buffering and increases ruminal pH (Allen, 1997). Ruminal pH reflects the ratio between acid production and absorption, thus increasing NDF intake per unit of fermentable starch in feedlot diets should increase ruminal pH or decrease the length of time pH is low (Galyean and Hubbert, 2014). However, it is unknown if these benefits result from the physical characteristics of traditional roughage sources or from the supply of dietary NDF diluting the starch concentration in the rumen. Because of this, the source of NDF required to buffer acid production in the rumen is unknown (Galyean and Hubbert, 2014), and the use of fibrous corn milling byproducts as a substitute for roughage needs further research.

Starch dilution may only affect DMI of high concentrate diets when the difference in fiber concentrations is large (Bartle et al., 1994), however when differences are small, changes in DMI that do occur are likely a result of changes in ruminal acidity or other digesta kinetics (Guthrie et al., 1996). This suggests that NDF concentration is positively related to DMI. Substitution of NDF from roughage with NDF from fibrous corn milling byproducts may adequately dilute the starch content of a feedlot diet and maintain performance, but further research is needed to determine the importance of the physical contribution of the fiber source to the regulation of the rumen environment.

Loerch (1991) evaluated the effect of replacing roughage in the diet with plastic pot scrubbers to determine the necessity of roughage in the diet. Three trials were completed to determine the effects of plastic pot scrubbers on feedlot performance and ruminal metabolism, the impact of the number of pot scrubbers, and the interaction between use of pot scrubbers and level of concentrate in the diet. Across all 3 trials, the plastic pot scrubbers used as a replacement for roughage did not negatively affect ruminal pH, VFA concentration, or ruminal dilution rate and volume. Loerch (1991) suggested that roughage could be completely removed from the diet and replaced with pot scrubbers without decreasing cattle performance. Cattle consuming a 100% concentrate diet with 4 to 8 plastic pot scrubbers had similar performance to cattle consuming an 85% concentrate and 15% roughage diet. However, cattle had decreased ADG when fed a 100% concentrate diet for an extended period (112 d) compared to cattle consuming 85% concentrate and 15% roughage (Loerch, 1991). It is also possible that roughages gradually contribute to rumen fill, thus minimizing the positive effects of greater DMI from roughage later in the feeding period (Galyean and Defoor, 2003). Thus, timing of the addition or removal of roughage in a feedlot diet may be worth investigating.

Loerch and Fluharty (1998) observed that liver abscesses doubled when decreasing roughage from 30% in the beginning to 15% in the middle and 0% late in the finishing phase compared to increasing roughage from 0% in the beginning to 15%, then 30% late in the finishing phase. In a study feeding high lipid and high fiber (HLP) byproduct pellets as a replacement for barley grain, the objective was to determine if timing and duration of feeding had an impact on performance and carcass characteristics over a 147-d feeding period divided into three, 49 d periods (Joy et al., 2016). A control, barley-based diet was compared to the HLP diets fed for different periods of time to finishing cattle. The HLP diet fed for the entire 147 d feeding period had the greatest DMI throughout the feeding period, and the lowest G:F. For steers fed the HLP diets for only the last 49 d of the feeding period, G:F and DMI did not differ from the control. The HLP diet fed for the last 49 d also had numerically greater HCW than the diets fed HLP for 98 or 147 d of the feeding period. Inclusion of high lipid and high fiber byproduct pellets in the later portion of the finishing period may improve carcass yield without impacting live performance as opposed to diets fed for the entire period, which increased DMI and did not improve performance. This suggests roughage could potentially be replaced with a non-roughage fiber source at the end of the finishing period without impacting DMI and feed efficiency, which is cost effective for feedlot producers.

Roughage in Feedlot Diets

Roughage in feedlot diets is typically limited to 8 to 10% of the diet on a DM basis to maintain rumen health while maximizing energy intake from concentrates. Improved ruminal buffering and greater DMI are frequently observed when feeding increasing levels of roughage to feedlot cattle, but these changes have not reliably resulted in performance improvements (Defoor et al., 2002; Quinn et al., 2011; Jennings et al., 2020). Diets with greater roughage and/or NDF concentrations might improve DMI because of changes in fermentation byproducts, ruminal acid load, papillae health, and digesta kinetics (Galyean and Hubbert, 2014). Alternatively, increasing roughage likely stimulates DMI by reducing propionate-induced satiety in feedlot cattle fed high concentrate diets. Regardless of the mechanism behind increased DMI, the greater intake associated with greater roughage concentrations is not likely to compensate for the energy diluting effect of roughage compared to feedstuffs such as processed grains (Galyean and Hubbert, 2014). Benton et al. (2010) evaluated the effects of increasing roughage inclusion in dry-rolled corn (DRC) and high moisture corn (HMC) based diets containing 30% WDGS. Steers receiving diets containing 4 or 8% roughage had greater DMI, final BW, and ADG compared to those consuming 0% roughage. This agrees with the positive linear relationship between DMI and dietary NDF observed by Galyean and Defoor (2003) and reported in a meta-analysis by Arelovich et al. (2008). In a more recent study evaluating the concentration of corn stalks in finishing cattle diets, increasing the proportion of corn stalks from 5 to 15% of DM decreased cattle performance despite similar metabolizable energy intake (Jennings et al., 2020). Hales et al. (2014) explained that feeding greater proportions of roughage increases fecal energy loss and reduces retained energy because of less efficient digestion and increased methane production. Alternatively, several studies indicate that roughage levels can be decreased in diets containing corn milling byproducts, like WCGF, without impacting cattle performance (Sindt et al., 2003; Farran et al., 2006; Parsons et al., 2007).

Increasing the amount of dietary roughage is also believed to mitigate acidosis and subsequent liver abscesses. Chibisa et al., (2020) evaluated increasing barley silage from 0 to 4, 8, or 12% of the diet, and observed an increase in rumination and mean pH, as well as decreased duration of time spent under pH acidosis thresholds (5.8, 5.5, and 5.2). Holland et al. (2018) reported that increasing dietary corn stalk concentrations from 7.1 to 19.1% of DM decreased the occurrence of liver abscesses, but negatively impacted growth performance and feed efficiency despite greater DMI of cattle consuming diets with higher roughage concentrations. In contrast, Kreikemier et al. (1990) reported that increasing roughage (50% alfalfa hay: 50% corn silage) from 0% to 5, 10, or 15% in steam rolled wheat diets did not influence liver abscess prevalence. In addition to overall roughage concentration, the physical form of the roughage source has been a major area of research in recent years, as increasing the concentration of dietary peNDF may provide additional benefits to rumen health and function that decrease the incidence of primary and secondary metabolic disorders.

Physically Effective Neutral Detergent Fiber

Mertens (1997) defined peNDF as the portion of NDF that stimulates mastication and consists of a combination of the NDF concentration and particle size to describe the proportion of a feedstuff that potentiates rumination. Characterizing fiber using both its physical and chemical properties and their contribution to rumination provides a more descriptive measurement of fiber than characterizing by NDF alone (Mertens, 1997). Measurement of peNDF has been widely used in dairy production, where diets consist of greater concentrations of roughage and NDF. However, its application to feedlot diets is not well researched and accurately calculating peNDF may be challenging in diets containing low proportions of traditional roughage and high concentrations of corn milling byproducts with high NDF content but small particle size. Particle size, in addition to NDF concentration, plays a large role in the contribution to peNDF and rumination activity. Greater particle size of traditional roughage promotes chewing, saliva secretion, and rumination, which buffers ruminal pH (Yang and Beauchemin, 2007).

The Penn State Particle Separator (PSPS) is a tool used to determine particle size distribution and calculate peNDF by separating a diet into 5 tiers. The PSPS is a 2-dimensional box containing 5 tiers with different sized pores: 1) 19.0-mm, 2) 8.0-mm, 3) 4.0-mm, 4) 1.18-mm, and 5) solid bottom (Lammers et al., 1996). Mertens (1997) uses 1.18-mm as the minimum particle size for a feedstuff to be considered “physically effective”. However, more recent research suggests that feed particles escaping the rumen may be as large as 4 mm (Heinrichs, 2013). To estimate peNDF, the amount of feed on the top 3 tiers (≥ 4 mm) is multiplied by the NDF content of the diet or feedstuff (Heinrichs, et al., 2013).

This calculation becomes difficult to apply to feedlot diets that contain fibrous corn milling byproducts with high levels of NDF, but small particle. In a recent study conducted at the West Texas A&M University Research Feedlot, replacing 20 to 30% of

SFC with WDGS and/or Sweet Bran increased peNDF concentrations, but did not impact rumination per kg of DMI (Spowart et al., 2020). Because of the nutritional and economic considerations of including roughage in a feedlot diet, developing an effective method to evaluate the roughage value of alternative fiber sources, such as corn milling byproducts, is important to establish minimum fiber recommendations for feedlot cattle (Mertens, 1997).

When evaluating the peNDF concentration of individual feed ingredients, Gentry et al. (2016) reported that long grind corn stalks (passed through a 7.62 cm screen once), had greater peNDF than short grind corn stalks (passed through a 7.62 cm screen twice), followed by WCGF and SFC. This agrees with previous research suggesting roughage sources, such as corn stalks, have greater peNDF than fibrous corn milling byproducts such as WCGF and WDGS. In addition to evaluating the peNDF concentration of individual ingredients, Gentry et al. (2016) fed 3 dietary treatments with different corn stalk grind sizes and inclusion levels: 1) 10% short grind (10SG), 2) 5% short grind (5SG), and 3) 5% long grind (5GL). Physically effective NDF was greatest for 10SG compared to 5SG and 5LG (13.0, 11.4, and 11.3% respectively). In this experiment, ADG did not differ among treatments, but DMI was greatest for cattle consuming 5LG and least for 10SG, which contradicts the concept that DMI increases with roughage concentration (Gentry et al., 2106). However, it may suggest peNDF content does not need to be greater to potentiate greater DMI or performance. In addition, greater peNDF is associated with increased ability of a feedstuff to stimulate rumination, but research suggests this may not be necessary to improve performance and provide ruminal buffering effects for feedlot cattle.

Rumination

Rumination is a defining characteristic for ruminant animals, and involves the regurgitation, rechewing, and swallowing of ruminal contents previously consumed by the animal (NASEM, 2016). Rumination stimulates saliva production to buffer rumen pH and aids in breaking down the size of feed particles to pass through the reticulo-omasal orifice (Welch, 1982). In addition, rumination provides rumen bacteria greater access to feed particles during microbial fermentation, as the surface area of feed particles is increased (Russell and Rychlik, 2001). Rumination follows a circadian rhythm, with most rumination occurring at night (Beauchemin, 1991). When consuming forage-based diets, cattle ruminate for roughly 8 to 9 h per d in 10 to 20 periods per day (Welch, 1982). In contrast, feedlot cattle consuming high concentrate diets ruminate 1.25 h per d (Beauchemin, 1994). Roughage is generally regarded as a requirement for cattle to ruminate (Galyean et al., 2014). However, although rumination time decreases drastically on all concentrate diets, it remains a natural urge for feedlot cattle (Beauchemin, 1991). Gentry et al. (2016) reported an increase in rumination time with increased concentrations of roughage in the diet. Steers fed 10SG had the greatest rumination (min/d) followed by 5LG and 5SG. Similarly, Weiss et al. (2017) observed that cattle consuming 10LG had the greatest rumination time and ruminal pH, followed by 5LG, which was greater than 5SG and 10SG. Both studies indicate long grind roughage may be included at a lower inclusion and still adequately stimulate rumination. However, the optimal roughage inclusion required to achieve maximized feedlot performance while maintaining rumination and ruminal pH is unknown.

Corn Milling Byproducts

In contrast to traditional roughage sources, fibrous corn milling byproducts such as WDGS, WCGF, and Sweet Bran (Cargill, Blair, NE) may increase DMI to a greater extent because of increased passage rate. Additionally, corn milling byproducts often contain similar energy concentrations and are fermented at a slower rate than processed grains, reducing the risk for acidosis without impacting cost of gain (Galyean and Hubbert, 2014). However, the roughage contribution of fibrous corn milling byproducts is not well defined for feedlot cattle and can be difficult to interpret because of differences in physical characteristics and nutrient concentrations, such as total starch, NDF, and peNDF (Spowart et al., 2022). When corn milling byproducts are used in feedlot diets, they replace starch as a protein and energy source, but also contain a high NDF content. In a recent study conducted at the West Texas A&M University Research Feedlot, replacing 20 to 30% of steam-flaked corn with WDGS and/or Sweet Bran increased peNDF concentrations, but did not impact rumination per kg of DMI (Spowart et al., 2020). Because the small particle size of fibrous corn milling byproducts does not stimulate rumination to the degree that roughage does, the high NDF concentration likely overestimates peNDF in feedlot diets. Despite similar rumination, cattle consuming corn milling byproducts had greater ruminal pH, which could be facilitated by starch dilution as a proportion of the processed grains were replaced with fibrous corn milling byproducts. These feedstuffs contribute to the nutritional value of a feedlot diet which improves performance, but research suggests there may be benefits to rumen health as well. The two primary methods of corn milling are wet milling and dry milling. The byproducts of each milling process differ in physical characteristics and nutrient composition (Erickson et al., 2010).

Corn Gluten Feed

Corn gluten feed is a byproduct of the wet milling process, which uses #2 grade corn to produce high fructose corn syrup intended for human consumption. In the wet milling process, the kernel is broken down into fiber, gluten, starch, germ, and solubles. Byproducts of the wet milling process can then be combined in several ways to produce different feedstuffs that can be used in animal agriculture (Blanchard, 1992). Corn gluten feed should not be confused with corn gluten meal, as corn gluten meal contains approximately 60% crude protein (CP), whereas WCGF contains approximately 16 to 23% CP (Erickson et al., 2010). Corn gluten feed is produced using the fiber or bran separated during the wet milling process, as well as the steep liquor, commercially known as condensed fermented corn extractives. It can be concentrated to a 50% DM dense liquid and sold as is however, most is used in the production of corn gluten feed (Blanchard, 1992). Bran can also be marketed as is, but because of the availability of steep liquor, bran is typically used to make WCGF, which can also be dried to produce dried corn gluten feed. However, WCGF is more commonly used in the feedlot industry (Samuelson et al., 2016). Crude protein content can vary greatly based on the amount of steep added to the bran. The greater the concentration of steep added to corn bran or germ meal, the greater the CP and energy concentration of the resulting byproducts, which can differ among wet milling plants (Erickson et al., 2010). Therefore, the nutrient profile of WCGF is inconsistent, but ranges from 40 to 60% DM and 14 to 24% CP.

Feeding WCGF in place of corn dilutes dietary starch and influences the rumen environment (Erickson et al., 2010). Wet corn gluten feed has a low starch content and high NDF, and NDF from WCGF is also more degradable than NDF from traditional roughage sources. Early research evaluating the impacts of replacing corn in finishing diets with WCGF was primarily completed in diets containing DRC (Stock et al., 2000). Improvements in performance and feed efficiency were observed by Ham et al. (1995), who evaluated WCGF as a replacement for DRC and reported that maximum gain and DMI were reached when WCGF replaced 35% of DRC on a DM basis. Similarly, Macken et al. (2003) observed the greatest performance and feed efficiency when 35% WCGF replaced SFC on a DM basis. Research by Scott et al. (2003) suggested that more extensive processing of corn fed in diets containing WCGF could further improve feed efficiency. For example, in a study evaluating WCGF in diets with different corn processing methods, steers that received diets containing WCGF had greater DMI when fed in combination with more extensively processed corn such as SFC. Steers consuming SFC based diets with 22% WCGF had 8% greater ADG and 9% greater feed efficiency compared to steers receiving diets that did not contain WCGF.

In addition to the high concentrations of energy and protein included in WCGF, this feedstuff also supplies large amounts of readily degradable fiber. Therefore, there has been some interest in evaluating if WCGF can be used to replace a portion of traditional roughage sources in the diet and/or if the concentration of roughage in the diet can be decreased when WCGF is used to replace processed grains. Parsons et al. (2007) conducted a study evaluating this concept by feeding a SFC based finishing diet with 40% WCGF, and decreasing roughage to either 9, 4.5, or 0%, compared to a control diet containing no WCGF and 9% roughage. Final BW was not different between the control and diets containing WCGF, however, a linear increase in DMI and BW was observed for cattle consuming diets containing WCGF and increasing roughage concentrations. Steers consuming 0% roughage had the lowest DMI and ADG, and G:F was not different than 4.5 or 9% roughage. There were also no differences in performance feeding 4.5 or 9% roughage, suggesting roughage levels can be decreased when feeding WCGF without negatively impacting performance. Additionally, Farran et al. (2006) reported an improvement in ADG when cattle were fed WCGF with 0% roughage, compared to diets with 0% roughage containing no WCGF. These studies suggest WCGF may have a ruminal buffering effect reducing the risk of acidosis and improving DMI and performance.

Distillers Grains with Solubles

In addition to byproducts of the wet milling industry, the expansion of the ethanol industry to provide a source of renewable fuels has made dry milling byproducts a viable option for use in finishing cattle diets as a source of both energy and protein (Klopfenstein et al., 2008). Distillers grains are one of the ethanol byproducts used worldwide to feed all species of livestock, and beef cattle account for 47% of distillers grain consumption, followed by dairy cattle at 31% (RFA, 2022). Distillers grains are efficiently used by ruminants and are the most common commercial feed product used in the United States today (RFA, 2022).

The dry milling process uses corn or other sources of starch such as wheat, barley, sorghum, milo, and sugar cane. When using distillers grains in feedlot diets, taking into consideration the source of starch is important because the nutrient profiles of each cereal grain will vary greatly (Erickson et al., 2010). Corn used for ethanol production, unlike wet milling, is sample grade and of lower quality. The milling process involves grinding the corn to a flour, and cooking in water at high temperatures to break down the protein matrix surrounding the starch granules and make them more available for fermentation (Winkler-Moser and Breyer, 2011). After fermentation, the leftover mash called whole stillage, consists of one-third of the original grain and is highly concentrated in nutrients. The whole stillage is processed through distillation columns to further refine the product and can then be separated via centrifugation into a liquid fraction and solid fraction (Stock et al., 2000). The liquid fraction is referred to as thin stillage, and the solid fraction is known as wet distillers grains (WDG), which can be dried for use as dried distillers grains. The thin stillage is then evaporated which results in a syrup-like substance containing 20 to 35% DM, known as condensed distillers solubles (Stock et al., 2000). The solubles can be dried and combined with dried distillers grains to produce dried distillers grain plus solubles, added to WDG to produce WDGS or sold alone as its own feed product (Stock et al., 2000).

A meta-analysis summarizing 20 trials suggested that inclusion rates of up to 40% are optimal for maximizing performance and carcass characteristics in feedlot cattle fed DRC or HMC based diets (Erickson et al., 2010). Improvements in G:F by 8% and ADG by 10% were also observed by Al-Suwaiegh et al. (2002) when increasing WDGS from 0 to 30% of diet DM in DRC based diets. Feeding WDGS in feedlot diets generally has a positive impact on feedlot cattle performance; however, the degree of processing of grains in the diet may influence the extent of improvements in performance. (Klopfenstein et al., 2008).

Oglesebee et al. (2016) evaluated the value of fiber, fat, CP, and WDGS solubles, and how the nutrients in WGDS contributed to the nutritional value of WDGS and subsequent performance. This study used 3 diets containing a 1:1 ratio of DRC and HMC with either 0, 20, or 40% WDGS. The other diets, also containing a 1:1 ratio of DRC and HMC, were formulated without WDGS and balanced to contain the same nutrient composition using different levels of corn bran, solvent extracted germ meal, corn gluten meal, whole fat germ, or condensed distillers solubles. As WDGS replaced the corn blend, there was a quadratic increase in final body weight (BW), hot carcass weight (HCW), DMI, ADG and a decrease in F:G (Oglesbee et al., 2016). Based on the performance of cattle consuming the diets not containing WDGS, the authors concluded that fiber is not the main contributor to improved performance when feeding WDGS, and no single nutrient added to diets without WDGS matched the feeding value of diets containing WDGS.

Overall, including WDGS in diets containing DRC has improved performance, but when WDGS is added to diets containing SFC, reduced performance is commonly observed. Luebbe et al. (2012) observed linear decreases in ADG and G:F when 15, 30, 45, and 60% WDGS were added to diets containing SFC. Daubert et al. (2005) considered the upper threshold of WDGS inclusion in SFC diets to be 15% on a DM basis to achieve the maximum G:F. In contrast, Depenbusch et al. (2008) fed WDGS at 25% inclusion rate on a DM basis, and no differences in performance were observed compared to diets fed no WDGS. It was concluded that variables such as starch availability and rumen pH, passage rate, and different fermentation characteristics of processed grains impact the feeding value of WDGS (Depenbusch et al., 2008).

Combination of Wet Corn Gluten Feed and Wet Distillers Grains with Solubles

Complementary nutrient profiles of WCGF and WDGS suggests there is potential for associative effects between these ingredients (Klopfenstein et al., 2008). However, improved performance when feeding a combination of corn milling byproducts has not been consistently observed. Loza et al. (2010) evaluated feeding a 1:1 byproduct blend of WCGF and WDGS at 15 and 30% compared to diets containing a single byproduct at 15 and 30% and reported no associative effects. Steers consuming both byproduct blends had greater ADG, G:F, and final BW than steers consuming diets containing no byproducts, and there was no improvement in performance compared to diets containing a single byproduct. An additional experiment by Loza et al. (2010) evaluated 0, 10, 15, 20, 25, and 30% WDGS in diets containing 30% WCGF. Increasing the concentration of WDGS resulted in a quadratic effect on DMI, where DMI was increased by 5.2% when feeding 15% WDGS compared to 0% WDGS. A quadratic response was also observed for ADG with the greatest increase observed at 15 to 20% inclusion. There was no quadratic relationship observed in G:F, although the greatest numerical values were also observed at 15 to 20% WDGS inclusion. Wet distillers grains are a source of protein, energy, and fiber, and can improve performance under some conditions. However, based on these experiments, there seems to be a limit to the value of WDGS in a finishing diet when fed beyond 40% inclusion.

Conclusions from the Literature

Processed grains are beneficial to feedlot cattle efficiency and performance; however, rapid fermentation of readily available starch can potentially lead to rumen dysfunction. Ruminal acidosis reduces cattle performance, erodes the ruminal epithelium, decreases the absorptive capacity of the rumen, and is believed to cause liver abscesses. Decreasing dietary starch load may provide a route to improve rumen health and increase DMI of feedlot cattle. For example, increasing the concentration of NDF from roughage in finishing diets has the potential to modulate ruminal pH, reduce the risk of metabolic disorders, and increase DMI but at the cost of loss in performance. In contrast to traditional roughage sources, fibrous corn milling byproducts such as WDGS and WCGF contain greater energy concentrations and may stimulate DMI to a greater extent because of increased passage rate and are fermented at a slower rate than processed grains. Fibrous corn milling byproducts dilute starch by replacing processed grains with readily digestible fiber and might have the ability to mitigate acidosis. However, these feedstuffs require further evaluation as a replacement for traditional roughage sources in feedlot diets because of differences in physical characteristics and peNDF content.

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Chapter II: Impacts of starch dilution with Roughage vs. Wet distillers grains with solubles post terminal reimplant on growth performance and carcass outcomes of feedlot cattle.

INTRODUCTION

Typical finishing cattle diets contain relatively low roughage concentrations and high proportions of processed grains containing readily fermentable starch to maximize performance, minimize cost per unit of energy, and improve feeding logistics (Brown et al., 2006; Samuelson et al., 2016). However, increasing the concentration of neutral detergent fiber (NDF) from roughage in finishing diets has the potential to modulate ruminal pH, reduce the risk of metabolic disorders, and increase dry matter intake (DMI). Improved rumen buffering and greater DMI are frequently observed when feeding higher roughage concentrations to feedlot cattle (Defoor et al., 2002; Quinn et al., 2011; Jennings et al., 2020), but these changes have not resulted in performance improvements because the greater DMI is unlikely to compensate for the energy diluting effect of roughage in most scenarios (Galyean and Hubbert, 2014). Increasing the proportion of dietary fat to balance the energy concentration of feedlot diets that incorporate greater concentrations of roughage may provide a route to improve finishing cattle performance, but it is cost prohibitive under current market conditions.

In contrast, fibrous byproducts such as wet distillers grains with solubles (WDGS), wet corn gluten feed (WCGF), and Sweet Bran (SB) contain greater energy concentrations than traditional roughage sources, may stimulate DMI to a greater extent because of increased passage rate, and are fermented at a slower rate than processed grains, thus decreasing the potential for acidosis while maintaining cost of gain (Galyean and Hubbert, 2014). However, the roughage contribution of fibrous byproducts is not well defined for feedlot cattle and can be difficult to interpret because of differences in the dietary formulations used in previous research and the nutrient and physical characteristics of traditional roughage sources vs. fibrous byproducts. However, research by Spowart et al. (2021) suggests that total dietary starch intake may play a more important role than the physical characteristics of the fiber source in regulating rumen environment, DMI, and subsequent cattle performance. Therefore, opportunities may exist to use fibrous byproducts in lieu of a traditional roughage source to reduce dietary starch and improve DMI and ruminal health, particularly at the end of the feeding period when digestive mortalities are most impactful. Furthermore, feedlot cattle performance and feed efficiency has been reported to decline with increasing days on feed and at the end of the finishing phase (Joy et al., 2016; Martinez et al., 2021). Management practices such as terminal sorting, re-implanting, and administration of β-adrenergic agonists are also commonly used in the latter portion of the feeding period and may impact overall DMI and eating behavior and negatively affect cattle performance. Our hypothesis was that decreasing the starch concentration of the diet would improve feedlot cattle growth and performance post terminal implant regardless of the dietary fiber source. Therefore, the objectives of this study were to: 1) determine the effects of starch dilution from terminal implant to slaughter on feedlot cattle performance and carcass characteristics and 2) quantify performance and carcass outcomes of cattle consuming diets containing similar energy and starch concentrations, but different sources of dietary fiber.

MATERIALS & METHODS

Receiving Cattle Management

All procedures involving animals were approved by the West Texas A&M University/Cooperative Research, Education, and Extension Team Institutional Animal Care and Use Committee (approval number 2021.10.002). Before initiation of the study, 400 crossbred steers and bulls (222 ± 1.8 kg) were purchased from an order buyer and received at the West Texas A&M University Research Feedlot (WTRF) from July 22 to August 12, 2021. At initial processing, calves were weighed individually to determine body weight (BW), given unique visual identification and electronic identification ear tags, ear-notched to determine persistent infection with bovine viral diarrhea virus, administered a Mannheimia haemolytica bacterin, (Nuplura; Elanco Animal Health), modified-live virus (Titanium 5, Elanco Animal Health) and clostridial plus tetanus (Cavalry 9, Merck Animal Health) vaccines. Cattle also received a growth-promoting implant (Component E-S with Tylan; 200 mg progesterone, 20 mg estradiol benzoate, and 29 mg tylosin tartrate, Elanco Animal Health) and metaphylactic treatment with tildipirosin (Zuprevo, Merck Animal Health). Anthelmintics were administered orally and parenterally for the treatment of external and internal parasites (Valbazen, Zoetis, Florham Park, NJ and Normectin, Norbook Labs, Overland Park, KS). Bulls were castrated using a castration band (Callicrate, St. Francis, KS) and orally administered 1 mg per kg BW of meloxicam (Unichem Pharmaceuticals, Hasbrouck Heights, NJ). After initial processing, calves were used for an unrelated, 56-d receiving study. At the end of the experimental period, cattle received a second dose of metaphylaxis with tulathromycin (Increxxa, Elanco Animal Health) to mitigate bovine respiratory disease. An additional 180 steers and bulls (213 ± 1.9 kg) were purchased from an order buyer and received at the WTRF on June 3, 2021. Cattle were processed upon arrival using the same procedures described previously, except they did not receive Nuplura or a secondary dose of metaphylaxis. These cattle were also used in an unrelated 56-d receiving study followed by a 72-d growing period that included administration of a second anabolic growth implant (Revalor XS, 40 mg estradiol and 200 mg trenbolone acetate, Merck Animal Health) at 84 days on feed (DOF). After completion of the respective receiving studies, steers were transitioned to a common finishing diet over 18 d using a two-ration system where the proportion of finishing diet was increased to replace 10% of the receiving diet every 2 d. Steers were fed the common finishing diet until initiation of the current study on November 5, 2021.

Animal Management and Treatments

A total of 416 crossbred steers were used in a randomized complete block design. Enrollment procedures were completed over 3 consecutive days to obtain an average initial body weight (BW; 372 ± 2.67 kg) and allocate cattle into their respective treatment pens. On d -2 of the study, steers were weighed individually and those that had not already received a second growth-promoting implant were re-implanted (Revalor XS, Merck Animal Health). Steers were then ranked by BW and randomly assigned to 48 pens in 12 BW blocks such that the average BW, BW standard deviation, and number of animals that had previously received antibiotic treatment for bovine respiratory disease were similar among pens. Because of limited availability of sort pens, on d -1 steers were individually weighed a second time to calculate initial BW (average of d -2 and d -1 BW), received a color-coded pen tag, and were physically allocated into 1 of 12 experimental blocks and housed overnight as a single pen. On d 0, the steers in each block were sorted into their respective treatment pens using the previously administered colored pen tag and the study was initiated. Therefore, the study consisted of 416 steers fed in 48 soil-surfaced pens (27.4 m × 6.10 m) arranged into 12 blocks with 4 pens per block and 8 or 9 animals within each pen. Within each BW block, steers were randomly assigned to 1 of 4 dietary treatments (n = 12 pens per treatment). Treatments (Table 1) were: 1) **CON**; a finishing diet containing 64.80% steam-flaked corn and 7.50 % corn stalks on a DM basis fed for the entire feeding period, 2) **CS** a finishing diet containing 55.10% steam-flaked corn and 14.75% corn stalks on a DM basis fed from terminal implant to slaughter, 3) **WD**; a finishing diet containing 54.70% steam-flaked corn, 9.50% wet distillers grains with solubles, and 7.50% corn stalks on a DM basis fed from terminal implant to slaughter, and 4) **NR** a finishing diet containing 54.20% steam-flaked corn, 19.00% wet distillers grains with solubles, and 0.00% corn stalks on a DM basis fed from terminal implant to slaughter.

Ingredients used in the present study were sourced within the Texas panhandle region. The WDGS used in the study were picked up two to three times per week from a commercial feedlot and sourced from White Energy. Differences in crop production in the high plains region can influence the raw materials used in the production of WDGS.

The WDGS are likely a blend of corn and grain sorghum, however the ratio is unknown. Corn stalks were sourced and ground by a commercial hay company (Reinhart Hay & Commodities), and the SFC was sourced from Dimmit Flaking LP.

Diets were formulated to contain similar concentrations of net energy for maintenance (NEm) and SB (20% of DM). Because of increasing fat prices and recent changes in industry practices with respect to feedlot diet formulations, less fat was used in the "CON" diet than that recommended by consulting feedlot nutritionists several years ago (Samuelson et al., 2016). However, this provided a unique opportunity to use dietary fat to balance for energy and still be within fat inclusion recommendations of consulting nutritionists while potentially avoiding negative impacts on fiber digestion, as the total fat concentration of all experimental diets was below 6.5% of DM (NASEM, 2016)

The CS diet contained greater concentrations of both NDF and fat, but lower total starch than CON. Dietary NDF was increased by supplying a greater proportion of corn stalks than CON. Similarly, the WD diet contained greater NDF, but similar fat (within 1%) compared to CON. The NDF concentration of the diet was increased by supplying greater WDGS compared to CON. The NR diet contained greater NDF but less fat and starch than CON. The CS, WD, and NR diets were formulated to contain similar starch concentrations to evaluate the benefit of providing greater fiber from either corn stalks (primarily physically effective fiber) or WDGS (primarily readily degradable fiber with a smaller particle size) on a starch equivalent basis. Using the dietary starch concentrations obtained from analysis of individual ingredients before initiation of the study (Servi-Tech Laboratories, Hastings, NE), the diets were formulated to supply 52.4, 44.9, 44.9, and

44.9% total starch for CON, CS, WD, and NR respectively. However, after samples of each diet were collected, analytical results of the dietary starch concentrations were 50.4, 43.6, 43.8, and 44.7% for CON, CS, WD, and NR.

Dietary treatments were assigned to each pen on d 0 (initial BW), but all steers received CON until an average of 83 d before slaughter (Fig. 1). After this initial feeding period, steers were weighed individually (transition BW) then transitioned to CS, WD, or NR over 6 d using a two-ration blending system where the proportion of the respective treatment diet was increased by 25% every 2 d to replace CON. Steers designated to receive CON consumed the same dietary treatment from d 0 to slaughter (initial to final). Completion of the dietary transition (100% of treatment diets fed) was scheduled to coincide with administration of a terminal re-implant. At re-implant, steers were removed from their home pen, administered a terminal growth promoting implant (Revalor-200, 200mg of trenbolone acetate and 20mg of estradiol, Merck Animal Health), and withheld from feed and water in sorting pens for 2 h to induce a "re-implant challenge" and mimic conditions that might occur in a commercial feedlot facility where a greater number of cattle are processed within each day. After re-implantation, cattle were returned to their home pens and immediately provided with 100% of 1 of the 4 dietary treatments. Dietary treatments were applied uniformly to pens of cattle within each block; date of re-implant and dietary treatment initiation was selected based on projected growth performance and an estimated final unshrunk BW of approximately 659 kg.

Feed Delivery and Bunk Management

Feed bunks were visually evaluated twice daily at 0630 and 2100 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 (Model 84-8, Roto-Mix, Dodge City, KS) or mounted feed wagon (Model 274-12, Forage Express Feed Mixer, Roto-Mix, Dodge City, KS) depending on batch size and delivered to each pen beginning at 0730. Daily feed delivery order was CON, CS, WD, and NR. Feed refusals were removed from the feed bunk when an excess > 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 ºC for 24 h to calculate daily DMI.

Data Collection and Laboratory Analysis

Samples of SB and WDGS were collected daily and composited by week for analysis of DM (100º C for 24 h) and nutrient content (Servi-Tech Laboratories). Other feed ingredients such as steam-flaked corn, corn stalks, and supplement were collected once weekly in duplicate. One sample was used to determine DM (100º C for 24 h) and adjust each diet formulation on an as-fed basis, whereas the other was composited monthly for nutrient analysis (Servi-Tech Laboratories). Diet samples were collected twice weekly and split into 2 portions. One portion was immediately analyzed for DM (100º C for 24 h), and the second portion was composited twice per month for complete nutrient analysis by a commercial laboratory (Servi-Tech Laboratories).

Approximately 83 d after steers were designated to received 100% of each dietary treatment, they were shipped to a commercial processing facility (Tyson Fresh Meats, Amarillo, TX). Similar to initial BW, final BW was calculated as the average BW over 2 consecutive days and adjusted using a 4% pencil shrink. Because of low incidence, morbidity and mortality were not reported; however, throughout the course of the study 13 steers died from respiratory illness, bloat, unknown causes, or were removed from the study due to poor growth performance or lameness (CON = 3, CS = 4, WD = 3, and NR = 3). Hot carcass weights and liver scores were collected on the day cattle were harvested; carcass data including marbling score, 12th-rib subcutaneous fat, longissimus muscle (LM) area, kidney-heat-pelvic fat (KPH) and quality grade were collected after a 28 to 30 h chill. All carcass data was collected by personnel from the West Texas A&M University Beef Carcass Research Center (Canyon, TX).

Statistical Analysis

Performance data and carcass data with continuous variables were analyzed as a randomized complete block design using the MIXED procedure of SAS (SAS Inst. Inc, Cary, NC). Categorical data such as liver scores and quality grades, were analyzed using the GLIMMIX procedure of SAS. Pen was considered the experimental unit for all dependent variables. Because CS, WD, and NR were not applied until approximately 89 d before slaughter, the BW recorded immediately before transition to the respective dietary treatments (transition BW) was included as a covariate in the model to account for random numerical differences in BW that may have occurred before treatment application. Thus, transition BW and diet were included in the model as fixed variables, and block was random. Treatment means were reported as least squares means ± standard error of the mean (SEM). Treatment differences were considered statistically significant when $P \leq 0.10$ and a tendency when $0.10 > P \leq 0.15$.

RESULTS & DISCUSSION

Feed Composition

Nutrient concentrations of individual feed ingredients sampled throughout the study are presented in Table 2.2. Average DM values for SB, WDGS, SFC, and corn stalks were 62.6, 36.9, 84.1, and 89.8% respectively. Complete diet moisture can be affected by all ingredients, but especially those with a greater moisture concentration, like WDGS. Increasing the moisture content of a diet may improve mixing ability, reduce separation of ingredients, and improve palatability. However, the moisture concentration of the diet may also negatively impact the longevity of feed manufacturing equipment and diet freshness and has been shown to limit intake in dairy cattle (Lahr et al., 1983). Therefore, the moisture content of corn milling byproducts should be considered when formulating feedlot cattle finishing diets. Crude protein (CP) concentrations for SB, WDGS, SFC, and corn stalks were 24.0, 31.6, 8.0, and 4.2% respectively. The average CP of SB used in this study is comparable with the average CP content of 23.8% reported in the NASEM (2016). In contrast, the CP concentration of WDGS is influenced by the proportion of solubles incorporated into the final feed product and can be highly variable. The tabular value reported for CP of WDGS is 29.1% CP (NASEM, 2016), which is slightly less than the 31.6% CP of WDGS observed in the present study.

In addition to the DM and CP concentration, the crude fat (CF) content of corn milling byproducts can also be a source of nutrient variability. The average CF concentrations of SB and WDGS were 3.4 and 7.3%, which is less than the 4.7% and 10.8% fat reported by the NASEM (2016). Fat concentrations can be influenced by the manufacturing process used to produce SB and WDGS, as varying amounts of fat are frequently extracted during the milling process and sold as a separate commodity (corn oil), which explains why the average CF is lower than that reported in the NASEM (2016). Crude fat concentrations for SFC and corn stalks were 3.4 and 0.6% respectively.

Although commonly included in feedlot diets as a source of protein and energy, corn milling byproducts also contain relatively high NDF content. The NDF concentration of SB and WDGS were similar, averaging 34.7 and 34.0% respectively. In contrast, the average NDF content of corn stalks are much greater than either corn milling byproducts (75.8% of DM). Additionally, the fiber from corn stalks is less digestible than SB and WCGF, as evidenced by the greater ADF concentration (48.9, 11.0, and 17.0% for corn stalks, SB, and WDGS, respectively). As expected, SFC contained a lower proportion of NDF (8.8% of DM) than corn stalks, WDGS, and SB, and is primarily used in the diet as a source of dietary energy.

The average total starch concentrations of SB, WDGS, and SFC were 9.9, 5.0, and 75.8% respectively (Table 2.2). Total starch of SB is not reported in the NASEM (2016); however, WCGF is estimated to contain 15.2% starch, which is greater than the value observed for SB in the current study. Total starch for WDGS and SFC were comparable to their tabular values, which average 6.1 and 76.2%, respectively (NASEM, 2016). Corn stalks averaged 1.1% starch which is much lower the 10.8% total starch concentration reported by the NASEM (2016). Corn stalks exhibited the highest coefficient of variation of all ingredients for total starch as well as CP and CF. This is likely because the stalks, cobs, and fines of the ground corn stalks are dispersed randomly and possess variable nutrients that may not all be represented in a single sample. Average starch availability for SFC was 57.0 and ranged from 51.0 to 61.0%, which is important to note as fluctuations in starch availability may increase the risk for acidosis and impact measurements of animal performance (Owens et al., 1998).

Performance and Carcass Characteristics

Initial BW, transition BW, and final BW did not differ ($P \geq 0.17$) among dietary treatments (Table 2.4). However, final BW was numerically greatest for CS, which may be of importance to cattle feeders (CON = 628, CS = 642, WD = 640, and NR = 634 kg) No difference ($P = 0.93$) in DMI was observed from d 0 to transition, during which all cattle were receiving the same diet (CON). However, from transition to final, DMI was greatest ($P < 0.01$) for CS, intermediate for WD and CON, and least for NR.

Greater DMI of cattle consuming CS agrees with research completed by Farran et al. (2006) and Jennings et al. (2020), in which DMI was improved by 0.40 to 1.0 kg by increasing the percentage of alfalfa from 0 to 7.5% (Farran et al., 2006) or corn stalks from 5 to 15% (Jennings et al., 2020) of dietary DM over the entire feeding period. In the current study, when the roughage concentration of the diet was increased from 7.50 to 14.75% for the CS treatment, DMI of cattle consuming CS was 0.33 kg greater than CON when fed from terminal re-implant to slaughter. In contrast, when roughage was completely removed from the diet, DMI was reduced (8.1 vs. 9.2, 8.9, and 8.9 kg for NR vs. CS, WD, and CON, respectively) compared to cattle consuming treatments that contained at least a portion of the diet as corn stalks. In SFC-based diets containing 40.0% WCGF and 9.0, 4.5, or 0.0% roughage, DMI decreased linearly as the concentration of alfalfa in the diet was reduced (Parsons et al., 2007). Similarly, DMI was less for cattle consuming a high moisture corn-based diet with 0% roughage compared to cattle consuming a 15% roughage diet (Loerch and Fluharty, 1998). Less DMI was also observed by Turgeon et al. (2010) when roughage was eliminated from a whole corn-based diet containing 8.8 to 10.1% roughage and no corn milling byproducts.

When evaluated over the entire feeding period, DMI of cattle receiving NR was less ($P < 0.01$) than CS, WD, and CON, but DMI did not differ among these 3 dietary treatments. Similar to DMI, metabolizable energy (ME) intake did not differ among treatments from initial to transition ($P = 0.94$); however, ME intake was greatest for CS, intermediate for WD and CON, and least for NR from transition to final ($P < 0.01$) Additionally, ME intake was less ($P < 0.01$) for NR than CS, WD, and CON from initial to final. Overall, these data suggest that increasing the proportion of roughage in a finishing diet stimulates DMI and ME intake, whereas, eliminating roughage reduced DMI and ME intake. Because CS, WD, and NR were formulated to contain similar concentrations of dietary starch, ME, and NE, this suggests that the fiber source in the diet plays an important role in regulating DMI.

One reason increasing the proportion of roughage in the diet is believed to stimulate DMI is that cattle consuming high concentrate diets will attempt to eat to a constant energy level (Galyean and Defoor, 2003). Because roughages contain less dietary energy, addition of these ingredients to high concentrate diets may stimulate DMI to compensate for the diluting effect of roughage and maintain energy intake (Galyean and Hubbert, 2014). Jennings et al. (2020) observed no difference in ME intakes of cattle consuming finishing diets containing 0, 10, or 15% of DM as corn stalks. However, in a similar study, feedlot cattle consuming 15% corn stalks tended to have greater ME intake than those consuming diets containing only 5% corn stalks (Jennings et al., 2021). In the studies conducted by Jennings et al. (2020) and Jennings et al. (2021), the ME density of the diet decreased as the proportion of corn stalks increased. However, in the current study, corn oil was added to the diets to obtain similar dietary ME concentrations among the treatment diets (3.07, 3.07, 3.08, and 3.10 mcal/kg for CON, CS, WD, and NR, respectively). Our hypothesis was that increasing the proportion of roughage in the diet would increase DMI and ME intake if diets did not differ in energy concentration. Therefore, the greater DMI and ME intake of cattle consuming CS suggests that perhaps a mechanism other than reduced dietary energy density influences DMI of cattle consuming diets containing increasing proportions of roughage.

In a meta-analysis of 11 experiments conducted in feedlot cattle consuming diets containing 7.5 to 35.3% roughage, Arelovich et al. (2008) reported that dietary NDF was positively related to both DMI and NEg intake. The concentrations of NDF in the present study were 18.4, 23.8, 21.3, and 17.7% for CON, CS, WD, and NR respectively. Although the dietary NDF concentration of CON and NR were similar, NR had lower DMI. Similarly, WD and CS had comparable NDF, yet CS had greater DMI, while WD and CON did not differ. This further suggests the nutrient content of the diet is not the only driving factor stimulating DMI.

Alternatively, increasing roughage may stimulate DMI by reducing propionate-induced satiety in feedlot cattle fed high concentrate diets (Galyean and Hubbert, 2014). Propionate, an end product of starch fermentation, is the primary fuel stimulating hepatic oxidation and satiety signaling in the ruminant (Allen et al., 2009). Propionate production is influenced by diet composition and fermentability. For example, forage-based diets typically result in a greater acetate to propionate ratio (NASEM, 2016). Pickinpaugh et al. (2021) observed that increasing the roughage concentration of the diet from 10 to 16% linearly decreased rumen propionate concentrations.

In addition to traditional roughage sources, starch concentration and diet fermentability can also be reduced by substituting processed grains with non-forage fiber sources, such as corn milling byproducts (Allen et al., 2009). However, replacing SFC with increasing levels of WDGS had no effect on propionate production in previous research (May et al., 2010b; May et al., 2011; Smith et al., 2013), suggesting WDGS may result in similar propionate production compared to SFC. This could potentially explain why DMI of WD did not differ from CON in the present study. However, cattle consuming the WD diet, which included a greater proportion of WDGS, lower proportion of SFC, and similar proportion of corn stalks compared to CON, had intermediate DMI compared to CS. Therefore, additional research is needed to evaluate the changes in rumen fermentation patterns of cattle consuming diets in which WDGS replaces a proportion of the roughage source, such as NR.

In addition to potential changes in fermentation end-products, greater DMI of cattle consuming CS could have resulted from the positive influence of greater dietary roughage concentrations on rumination and ruminal pH. Sindt et al. (2003) observed a linear increase in ruminal pH when increasing the dietary roughage concentration from 0 to 6% on a DM basis. Decreasing dietary starch concentrations with either roughage or fibrous corn milling byproducts has been shown to increase ruminal pH (Spowart et al., 2022). However, the physical characteristics provided by traditional roughage sources could further influence the rumen environment. Gentry et al. (2016), Weiss et al. (2017), Jennings et al. (2020), and Jennings et al. (2021) all reported that increasing the proportion of corn stalks in the diet increases rumination minutes in feedlot cattle. Therefore, it is possible that the greater proportion of corn stalks in CS increased chewing time and production of saliva from rumination, thus providing additional buffering capacity and increasing ruminal pH beyond what would be provided by simply decreasing the starch content of the diet (Allen et al., 1997).

Inclusion of corn milling byproducts such as SB and WDGS in feedlot diets may have the potential to dilute dietary starch and buffer rumen acidity because of the low starch and high NDF concentrations contained in these ingredients. However, this does not explain why DMI did not differ between WD and CON when the dietary starch concentrations were 6.6% less, and DMI was greater for CS than WD when the starch concentrations were similar. Furthermore, DMI of NR was less than CS, WD, and CON. This indicates that either WDGS did not provide the same buffering capacity as corn stalks or that the buffering capacity contributed by the diet did not influence DMI.

The ADG of cattle consuming CON, CS, WD, and NR was not different from initial to transition, transition to final, or initial to final ($P \geq 0.18$). Because DMI and ADG did not differ from initial to transition, no difference in G:F was observed during this time period ($P = 0.64$). However, from transition to final G:F was greatest ($P = 0.10$)

for NR, intermediate for WD, and least for CS and CON. From initial to final, G:F tended to be greater (*P* = 0.14) for NR than CS, WD, and CON.

Cattle consuming diets with increasing concentrations of roughage typically have lower ADG despite increased DMI (Bartle et al., 1994; Gentry et al., 2016; Jennings et al., 2020). This is likely a result of the decreased energy density of the diet. Jennings et al. (2020) observed that increasing the proportion of corn stalks from 5 to 15% of DM decreased ADG, despite similar ME intake. Hales et al. (2014) explained that feeding greater proportions of roughage increases fecal and gaseous energy loss and reduces retained energy. In the current study, the diets were formulated to contain similar concentrations of ME and NE by adding corn oil. As a result, cattle consuming CS had greater ME intake, but ADG and G:F did not differ from CON. Because cattle performance was not negatively impacted by increasing the dietary roughage concentration, using high energy ingredients such as fat to balance the energy concentration may be a strategy to improve performance of finishing cattle consuming diets that incorporate greater proportions of roughage. However, additional research is needed to validate this hypothesis. Increasing the proportion of WDGS in the WD and NR diets did not influence ADG compared to CON in the present study. In previous research, replacing SFC with WDGS resulted in either no performance improvement or negatively impacted performance of finishing cattle (Daubert et al., 2005; Depenbusch et al., 2008; Luebbe et al., 2012). In agreement with the performance outcome of cattle consuming WD, Spowart et al. (2020), also reported that adding 10% WDGS to SFC-based diets containing 20% SB did not influence DMI, ADG, or G:F.

Farran et al. (2006) reported that adding 35% WCGF to diets containing 0% roughage increased ADG, DMI, and G:F compared to diets containing 0% roughage and 0% WCGF. When proportions of both corn stalks and SFC were replaced with WDGS in NR, DMI was reduced but ADG did not differ, which resulted in an improvement in G:F. Benton et al. (2015) fed 30% WDGS in diets containing no roughage and observed decreased DMI and a tendency for lower ADG compared to diets containing 4 to 5% roughage. Similar to our observation for NR, because the DMI in Benton et al. (2015) was decreased to a greater extent compared to ADG, G:F was improved when roughage was removed from the diet. Likewise, Loerch and Fluharty (1998) also reported improved G:F in steers fed 100% concentrate, 0% roughage diets, from lower DMI and no difference in ADG. The greater G:F of cattle consuming NR is likely because of more efficient digestion and nutrient utilization. Digestibility has been reported to be less in diets containing increasing concentrations of roughage (Hales et al., 2014; Benton et al., 2015; Weiss et al., 2017). Lower digestibility likely occurred because of greater fecal energy loss and decreased NDF digestion. Methane energy loss also linearly increased with increasing roughage concentrations (Hales et al., 2014).

In the present study, no difference in HCW or dressing percentage was observed ($P \geq 0.24$; Table 2.4.). This agrees with Pickinpaugh et al. (2021) who reported no difference in HCW for finishing cattle consuming a 10, 12, 14, or 16% mixture of grass hay and straw. Dressing percentage can be negatively impacted by greater gut fill with increasing concentrations of roughage in a feedlot diet (Simóes et al., 2005). Roughage is much less fermentable than processed grains and may be retained in the digestive tract for a longer period of time, which could increase gut fill. However, the lack of difference in dressing percentage suggests there were no differences in gut fill between diets containing varying concentrations of SFC, corn stalks, and WDGS.

Marbling score was not different (*P* = 0.32). However, 12th rib fat thickness was greater (*P* = 0.10) for CS than WD, NR, and CON. The greater 12th rib thickness observed in cattle consuming the CS treatment is likely related to the numerically greater ADG of cattle consuming that diet. Alternatively, although not measured in the current study, increasing the concentration of roughage in the diet influences the end-products of microbial fermentation and may shift the composition of VFA's towards a greater proportion of ruminal acetate (Pickinpaugh et al., 2021). Because acetate is a precursor for fat synthesis (Park et al., 2018), if ruminal acetate was increased in the present study as a result the greater roughage concentration in CS, it is possible that these changes in the VFA profile compared to the other dietary treatments may have influenced fat deposition to some degree. Percentage KPH fat did not differ (*P* = 0.47) among cattle consuming CON, CS, WD, or NR. Given the greater 12th rib fat of CS, no difference in KPH fat is interesting provided that visceral fat is typically deposited before subcutaneous fat. There was no difference in LM area, yield grade, or quality grade among treatments ($P \geq 0.35$)

The proportion of A+, A, A-, or abscessed livers was not different ($P > 0.26$). While not fully understood, the etiology of liver abscess formation explains that liver abscesses commonly occur secondary to rumenitis caused by ruminal acidosis from the rapid ingestion of high amounts of readily available starch (Nagaraja and Chengappa, 1998). Therefore, increasing the concentration of dietary fiber, particularly from physically effective fiber sources such as corn stalks, is believed to reduce the prevalence of liver abscesses. By this logic, NR should have experienced the greatest percentage of abscessed livers, and CS the least. The lack of difference in the proportion of liver abscesses among dietary treatments disagrees with Bartle et al. (1994), Loerch and Fluharty (1998), and Holland et al. (2018) who observed reduced liver abscesses with increasing roughage concentrations. Because liver abscesses occur at low frequencies, treatment differences are difficult to detect in small sample size studies. Therefore, differences among treatments may have been detected with a larger sample size, increased pen replications, or if dietary treatments were fed longer, as opposed to only after administration of the terminal re-implant.

CONCLUSION

Corn milling byproducts are commonly used as a source of protein and energy in feedlot diets. However, because of their high NDF content, there is interest in evaluating the impact of substituting traditional roughage sources with corn milling byproducts, such as WDGS and SB, as well as the timing of substitution. Results of the present study suggest that diluting dietary starch with corn milling by products as a fiber source post-terminal implant does not improve feedlot cattle DMI or performance. However, increasing the roughage concentration of the diet post-terminal implant increased DMI and did not negatively impact ADG or G:F. Previous research consistently reports that increasing the dietary roughage concentration in finishing cattle diets stimulates DMI; however, more research is needed to evaluate the mechanism controlling these changes. In contrast, eliminating roughage from the diet post-terminal implant reduced DMI, did not impact ADG, and increased G:F. However, HCW was numerically least for cattle consuming diets containing 0% roughage. Carcass characteristics were not affected by roughage or byproduct inclusion level, except greater 12th rib fat thickness. The current paradigm for liver abscess pathogenesis suggests liver abscesses may be reduced by increasing roughage in a feedlot finishing diet; however, there was no statistical reduction in liver abscesses in this study when dietary roughage was increased, nor an increase in liver abscesses when roughage was removed from the diet. The results of this study suggest roughage stimulates intake and improves HCW when formulated to a similar energy density as diets containing no roughage. However, more information is needed to determine if it is economically beneficial, because although removing roughage decreased HCW, it improved G:F.

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Table 2.1. Ingredient composition and nutrient analysis of finishing diets including increased corn stalks, wet distillers grains with solubles, and no corn stalks.

	Treatments			
Item	CON	CS	WD	NR
Ingredient, % of DM				
Corn grain, flaked	64.8	55.1	54.7	54.2
Sweet Bran	20.0	20.0	20.0	20.0
WDGS	0.0	0.0	9.5	19.0
Corn Stalks	7.50	14.75	7.50	0.00
Corn Oil	1.10	3.52	1.75	0.22
Molasses Blend[1]	2.50	2.50	2.50	2.50
Supplement[2]	4.10	4.10	4.10	4.10
Nutrient Composition, DM basis[3]				
Dry Matter, %	78.1	78.7	70.3	63.6
TDN, %	89.8	85.8	88.3	92.3
NDF, %	18.6	22.6	21.2	18.4
rNDF[4]	5.7	11.2	5.7	0.0
peNDF, %[5]	8.9	10.7	8.0	5.9
ADF, %	8.5	12.2	10.2	7.5
Crude Protein, %	14.1	14.2	15.3	16.8
Crude Fat, %	4.6	6.5	5.6	4.8
Total Starch, %	50.4	43.6	43.8	44.7
ME, Mcal/kg[6]	3.07	3.07	3.08	3.10
NEm, Mcal/kg[6]	2.11	2.11	2.12	2.13
NEg, Mcal/kg[6]	1.45	1.44	1.45	1.47

[1]72 Brix Molasses Blend (Westway Feed Products LLC, Hereford, Texas).
[2]Formulated to meet or exceed NASEM requirements for vitamins and minerals (NASEM, 2016) and supplied 39.3 mg/kg monensin sodium and 9 mg/kg tylosin phosphate on a DM basis.
[3]Analyzed and calculated by Servi-Tech Laboratories (Hastings, NE).
[4]Roughage NDF = Corn stalks inclusion % × NDF % of corn stalks
[5]peNDF was calculated by multiplying the percentage of weight (DM basis) from the top 3 sieves
[6]Formulated using tabular values (NRC, 2000).

Table 2.2. Individual feed ingredient nutrient composition of finishing diets containing different concentrations of corn milling byproducts and corn stalks.

Item	SB[1]	WDGS[2]	SFC[3]	CS[4]
n	26	26	6	6
Nutrient, % of DM[5]				
DM				
Mean	62.6	36.9	84.1	89.8
Minimum	60.0	33.4	82.6	87.1
Maximum	66.7	40.4	85.5	91.7
CV[6]	2.6	5.2	1.3	2.0
CP				
Mean	24.0	31.6	8.0	4.2
Minimum	21.8	29.4	7.2	2.4
Maximum	25.4	34.1	8.9	6.3
CV[6]	3.8	3.5	7.5	33.3
Fat				
Mean	3.4	7.3	3.4	0.6
Minimum	2.5	6.3	2.6	0.2
Maximum	4.4	9.9	4.8	1.4
CV[6]	8.8	9.6	20.6	66.7
NDF				
Mean	34.7	34.0	8.8	75.8
Minimum	30.5	31.2	7.4	69.9
Maximum	37.4	37.1	10.1	83.0
CV[6]	5.2	5.0	10.2	6.3
ADF				
Mean	11.0	17.0	3.2	48.9
Minimum	9.1	13.8	3.0	41.9
Maximum	12.2	22.8	3.7	55.8
CV[6]	5.45	15.9	9.4	10.2

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

Table 2.3. Total starch and starch availability of individual ingredients in finishing diets containing different concentrations of corn milling byproducts and corn stalks.

Item	SB[1]	WDGS[2]	SFC[3]	CS[4]
n	26	26	6	6
Total Starch[5], %				
Mean	9.9	5.0	75.8	1.1
Minimum	6.0	3.0	74.2	0.3
Maximum	12.7	6.7	76.7	2.3
CV[6]	17.2	22.0	1.2	72.7
Starch Availability[5], %				
Mean	-	-	57.00	-
Minimum	-	-	51.00	-
Maximum	-	-	61.00	-
CV[6]	-	-	7.02	-

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

Table 2.4. Effects of diets containing no corn stalks, corn stalks, wet distillers grain with solubles and/or Sweet Bran on finishing cattle performance post terminal implant.

	Treatments[1]					
Item	CON	CS	WD	NR	SEM[2]	*P*-value
Shrunk BW, kg[3]						
Initial	360	360	360	360	15.88	0.83
Transition	524	521	514	520	3.68	0.17
Final	638	642	640	634	3.28	0.21
DMI, kg						
D0 to Transition	8.60	8.59	8.63	8.52	0.16	0.93
Transition to Final	8.90[b]	9.23[a]	8.88[b]	8.13[c]	0.14	<0.01
D0 to Final	8.69[a]	8.85[a]	8.71[a]	8.28[b]	0.11	<0.01
ME Intake, Mcal/d[4]						
D0 to Transition	26.3	26.3	26.4	26.1	0.53	0.94
Transition to Final	27.5[a]	28.7[a]	27.5[a]	25.4[b]	0.47	< 0.01
D0 to Final	26.7[a]	27.2[a]	26.8[a]	25.5[b]	0.34	< 0.01
ADG, kg						
D0 to Transition	1.55	1.57	1.55	1.56	0.02	0.34
Transition to Final	1.33	1.38	1.37	1.29	0.04	0.18
D0 to Final	1.44	1.47	1.45	1.42	0.02	0.19
G:F						
D0 to Transition	0.181	0.183	0.179	0.184	0.004	0.64
Transition to Final	0.150[b]	0.150[b]	0.154[ab]	0.158[a]	0.004	0.10
D0 to Final	0.166	0.166	0.167	0.172	0.003	0.14

[1] CON = control, 7.50% corn stalks and no wet distillers grain with solubles; CS = 14.75% corn stalks, no wet distillers grain with solubles; WD = 9.50% wet distillers grain with solubles; NR = no corn stalks and 19.00% wet distillers grain with solubles.
[2] Standard error of the mean.
[3] Calculated using a 4% shrink (BW × 0.96).
[4] ME intake was calculated as ME (Mcal/kg) × DMI (kg/d).

Table 2.5. Effects of diets containing sweet bran, corn stalks, wet distillers grain with solubles and no corn stalks on finishing cattle carcass characteristics.

	Treatments[1]					
Item	CON	CS	WD	NR	SEM[2]	*P*-value
HCW, kg	418	421	419	415	2.42	0.24
Dressing, %	65.6	65.6	65.4	65.4	0.24	0.93
Marbling Score[3]	47.1	47.0	45.3	46.0	1.21	0.43
12th -rib S.C. fat, cm	1.41[b]	1.54[a]	1.41[b]	1.40[b]	0.04	0.08
LM area, cm^2	106	105	103	104	1.79	0.32
KPH, %	2.21	2.27	2.21	2.23	0.14	0.47
Yield Grade[4]	2.59	2.79	2.68	2.67	0.11	0.35
Quality Grade, %						
Prime	0.8	1.8	2.3	0.0	-	0.43
Premium Choice	29.2	27.2	19.5	28.5	-	0.42
Choice	45.2	42.3	44.3	42.1	-	0.96
Select	24.8	28.7	33.9	29.4	-	0.57
Liver Score, %						
A+	5.19	4.18	9.39	5.90	-	0.56
A	0.20	1.12	1.58	0.92	-	0.78
A-	9.22	14.51	15.16	12.73	-	0.67
Abscessed, %	14.64	19.82	26.08	19.55	-	0.26

[1] CON = control, 7.50% corn stalks and no wet distillers grain with solubles; CS = 14.75% corn stalks, no wet distillers grain with solubles; WD = 9.50% wet distillers grain with solubles; NR = no corn stalks and 19.00% wet distillers grain with solubles.

[2] Standard error of the mean.

[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.

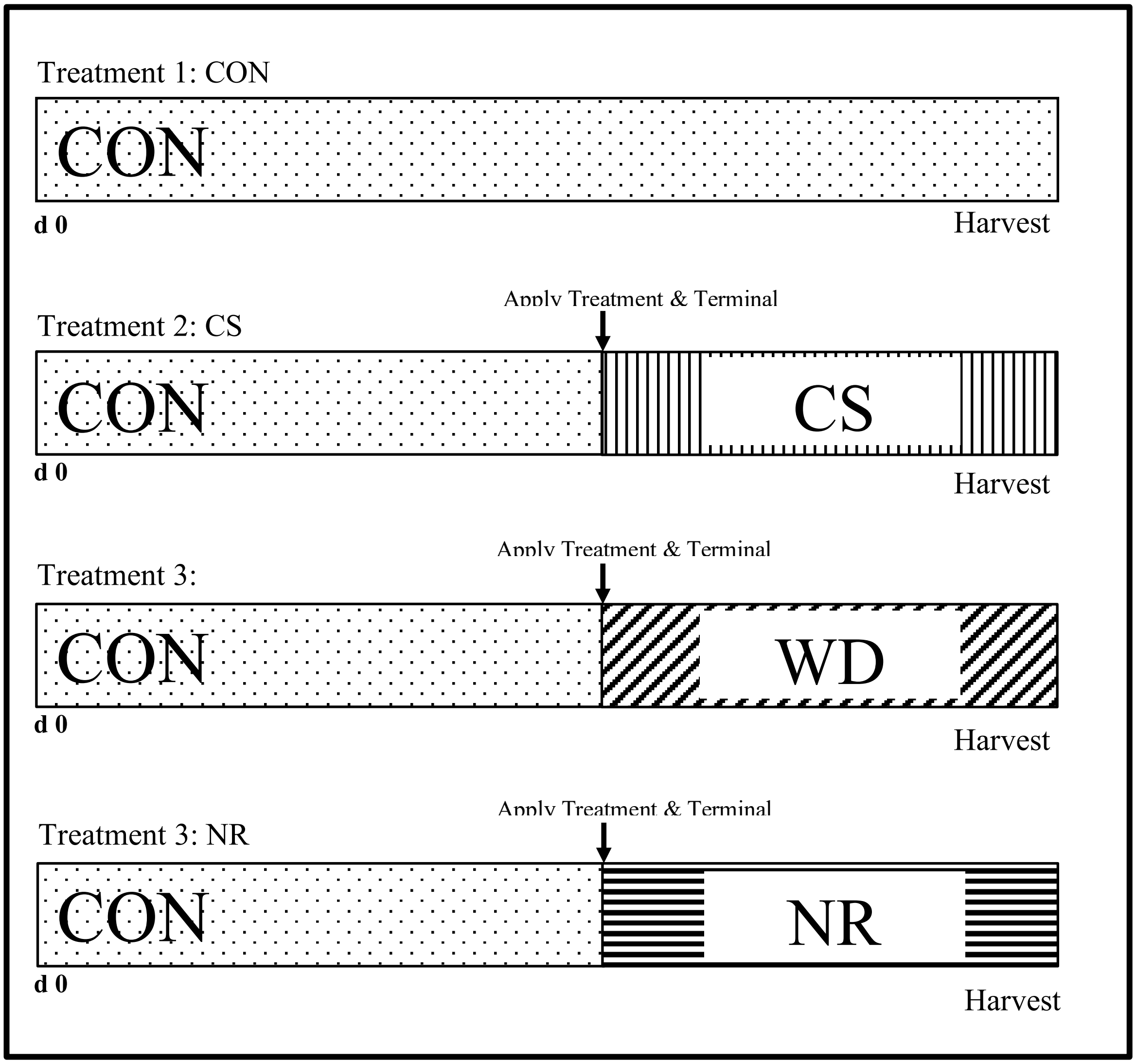

Figure 2.1. Application and timing of diets containing sweet bran, corn stalks, wet distillers grain with solubles and no corn stalks in finishing cattle.

Chapter III: Impacts of starch dilution with Roughage vs. Wet distiller's grains with solubles post terminal implant on ruminal buffering characteristics and ruminal integrity of feedlot cattle.

INTRODUCTION

Maintenance of ruminal health and integrity are fundamental components of achieving optimal performance in feedlot cattle. However, to maximize performance and minimize the cost per unit of energy in feedlot diets, feeding high concentrations of processed grains containing readily available starch is a common management practice (Brown et al., 2006; Samuelson et al., 2016). Rapid fermentation of diets containing high concentrations of fermentable starch results in excess volatile fatty acid (VFA) production that alters the rumen environment and causes metabolic disorders such as ruminal acidosis. Ruminal acidosis is characterized by a low pH that causes papillae damage, erosion of the ruminal epithelium, and reduces absorptive capacity (Owens et al., 1998). Feedlot cattle are most at risk for metabolic disorders such as ruminal acidosis at 2 points during the finishing period; transition from a high roughage receiving diet to a finishing diet containing greater concentrations of readily fermentable starch, and towards the end of the finishing period (Castillo-Lopez et al., 2014). In addition to dietary factors, digestive upset caused by ruminal acidosis can occur in response to feeding events and/or changes in eating behavior that alter rumen fermentation. Management practices such as terminal sorting, re-implant administration, and provision of a β-adrenergic agonist are common in the latter portion of the finishing period (Samuelson et al., 2016) and may influence consumption patterns and risk of ruminal acidosis. As dry matter intake (DMI) increases with days on feed, cattle sensitivity to fluctuations in dietary starch content and intake patterns also increases, thus exacerbating the challenge of balancing rumen VFA production and utilization (Castillo-Lopez et al., 2014).

Increasing the concentration of neutral detergent fiber (NDF) from roughage and/or fibrous grain-milling products such as wet distillers grains with solubles (WDGS), wet corn gluten feed, and Sweet Bran (SB) in finishing cattle diets has the potential to modulate ruminal pH, reduce the risk of metabolic disorders, and increase DMI (Ham et al., 1994; Krehbiel et al., 1995, Domby et al., 2014; Spowart et al., 2022). However, the roughage contribution of fibrous grain-milling products is not well defined for feedlot cattle and can be difficult to interpret because of differences in characteristics such as total starch, neutral detergent fiber (NDF), and physically effective NDF (peNDF).

Physically effective NDF uses a combination of the total NDF concentration and particle size to describe the proportion of a feedstuff that potentiates rumination. Greater particle size promotes chewing, saliva secretion, and rumination, which buffers ruminal pH (Yang and Beauchemin, 2007). Fibrous byproducts are a source of NDF in feedlot diets but have small particle size. Spowart et al. (2020) conducted a study replacing 20 to 30% of steam-flaked corn (SFC) with WDGS and/or SB and increased peNDF concentrations but did not impact rumination minutes per kg of DMI. Despite similar rumination time, ruminal pH increased as processed grains were replaced with fibrous byproducts (Spowart et al., 2020). In contrast, when corn stalks (CS) were increased from 5 to 10% by removing SB, dietary peNDF and rumination were greater but ruminal pH did not differ (Jennings et al., 2020). This suggests that the overall starch concentration of the diet may play a more important role in ruminal pH modulation than the characteristics of the fiber source. Decreasing dietary starch load may provide a route to improve rumen health and integrity, but additional research is needed to determine the value of traditional roughage sources compared to fibrous byproducts such as WDGS. Our hypothesis was that decreasing the starch concentration of the diet would increase ruminal pH and decrease the occurrence of ruminal scarring and lesions regardless of the fiber source used. Therefore, the objective of this study was to determine the effects of starch dilution with CS vs. WDGS from terminal implant to slaughter on rumination, ruminal buffering capacity, and physical integrity of the rumen.

MATERIALS & METHODS

Animal Management and Treatments

All procedures involving animals were approved by the West Texas A&M University/Cooperative Research, Education, and Extension Team Institutional Animal Care and Use Committee (approval number 2021.10.002). For this study, crossbred steers (n = 580) were received at the West Texas A&M University Research Feedlot and used in 2 unrelated 56-d receiving studies. After completion of the receiving studies, 416 of the most uniform steers were stratified into 12 body weight (BW) blocks over 3 consecutive days and allocated to 48 soil-surfaced pens (27.4 × 6.10 m) with 8 or 9 steers per pen in a randomized complete block design. Pens of cattle were randomly assigned to 1 of 4 dietary treatments within each BW block. Treatments (Table 2.1) were: 1) **CON**; a finishing diet containing 64.80% steam-flaked corn and 7.50 % CS on a DM basis fed for the entire feeding period, 2) **CS**; a finishing diet containing 55.1% steam-flaked corn and 14.75% CS on a DM basis fed from terminal implant to slaughter, 3) **WD**; a finishing diet containing 54.7% steam-flaked corn, 9.50% WDGS, and 7.50% CS on a DM basis fed from terminal implant to slaughter, and 4) **NR**; a finishing diet containing 54.2% steam-flaked corn, 19.00% WDGS, and 0.00% CS on a DM basis fed from terminal implant to slaughter. The CS, WD, and NR diets were formulated to contain less dietary starch than CON by increasing the concentration of either CS or WDGS. Additionally, CS, WD, and NR were formulated to contain similar concentrations of starch to determine the impact of altering the inclusion rate of fibrous ingredients independent of changes in starch concentration.

On average, 83 d before slaughter (minimum = 79 d; maximum = 92 d), all steers received a terminal re-implant (Revalor-200, 200 mg of trenbolone acetate and 20 mg estradiol, Merck Animal Health, Kenilworth, NJ) and were held in sorting pens with no access to feed and water for 2 h to mimic conditions that might occur during re-implant in a commercial feedlot. Six days before administration of the implant, steers consuming CS, WD, and NR began transition to their respective treatments diets from CON using a programmed two-ration system where the proportion of the treatment diet was increased by 25% every 2 d. This was completed such that steers were consuming 100% of each treatment diet on the day of terminal re-implant administration. In contrast, the CON steers consumed the same diet for the entire study (Fig. 1). Feed bunks were evaluated each day at 0630 and 2100 to determine the amount of feed to offer each pen and feeding began at 0730 using the feeding order CON, CS, WD, and NR. Any feed remaining when the bunk condition was visually evaluated at 0630 was removed, weighed, and analyzed for DM (100° C for 24 h in a forced air oven) to calculate daily DMI. Once all cattle within a block reached an unshrunk BW of approximately 659 kg, they were shipped to a commercial meat packing facility (Tyson Fresh Meats, Amarillo, Texas). The effects of the dietary treatments on performance parameters such as DMI, ADG, and G:F, and the results for carcass characteristics are presented in Chapter 2.

Technology Administration

To quantify ruminal pH and rumination, a subset of 2 steers per pen from the lightest 8 blocks (n = 64; 16 per treatment) were randomly selected to receive an indwelling ruminal pH bolus (smaXtec pH Plus Bolus SX. 1, SmaXtec, Graz, Austria) to quantify rumen pH, and a 3-axis accelerometer ear tag (SCR, Allflex Livestock Intelligence, Madison, WI) to quantify rumination and activity minutes. Technology was administered 56 d before administration of the terminal re-implant and 100% of the dietary treatments to provide "baseline" information regarding ruminal pH and rumination when all animals were consuming the same diet (CON). However, to allow for calibration of the technology after administration, only data from 28 d before the re-implant and treatment application is reported. Therefore, the data presented includes a baseline period from 28 d before re-implant and treatment application to initiation of the dietary transition (d 0 to 22), the dietary transition (d 22 to 28), and the period from re-implant to harvest when all cattle were receiving 100% of their respective dietary treatments (d 28 to 107). The data terminated on d 107 so that each block was represented in the data set as harvest date differed by block.

Data Collection and Laboratory Analysis

To determine the peNDF concentration of each treatment diet, 2 fresh samples of each diet were collected once per week. One sample was used for NDF and DM analysis (Servi-Tech Laboratories, Hastings, NE), and the second sample was used to determine the particle size distribution of each diet using the Penn State Particle Separator (PSPS; Lammers et al., 1996) and to calculate peNDF. Approximately 400 g of each diet was shaken for a total of 40 repetitions through 4 screens with varying diameters (19.0, 8.0, 4.0, and 1.18 mm). The peNDF was then calculated by weighing the contents of each screen and multiplying the percentage of weight from the top 3 screens (particles > 4.0 mm) by the NDF concentration of the diet and expressed as a percentage. The data reported for NDF, particle size distribution, and peNDF included a total of 26 samples from each diet.

Ruminal pH and rumination data were collected and managed according to the methods previously described by Crawford et al. (2022). Ruminal pH data was electronically logged in 10 min intervals. Daily ruminal pH was calculated as the average daily pH value, whereas hourly pH was averaged in 2 h intervals to coincide with rumination. Rumination data was logged in 2 h intervals as the total minutes spent ruminating in each 2 h period. Daily rumination minutes were calculated by averaging the total rumination minutes recorded within each 2 h interval per day, multiplied by 12 to adjust the value to a 24 h period. Rumination per kg of DMI was then calculated by dividing the total rumination minutes measured each day by the daily DMI. Hourly rumination was reported as the average of rumination minutes in each 2 h interval. The data reported for both hourly ruminal pH and rumination only represents the time from d 28 to harvest, when all cattle were consuming 100% of their respective treatment diets.

Immediately after harvest, a 5 × 5 cm^2 sample was collected from the rumen of each animal in the subset designated to receive technology devices. Samples were collected from the ventral sac of the rumen, approximately 10 cm from the cranial pillar. After collection, the tissue sample was immediately placed on ice, then washed gently with saline (Sodium Chloride 0.90%, VWR, Radnor, PA) to remove particulate matter. After cleaning, the sample was pinned and placed in a 1.0 L polypropylene bottle containing 850 mL of 10% neutral buffered formalin (VWR, Radnor, PA) to obtain a 20:1 ratio of formalin to sample and stored at ambient temperature. Samples were later shipped to the ruminant nutrition laboratory at the University of Saskatchewan (Saskatoon, SK, Canada) for analysis of morphological and histological characteristics (data not shown).

In addition to collecting ruminal tissue from the subset of steers with technology devices, the rumen was visually evaluated for the presence of lesions, scarring, and other abnormalities. Rumens were washed with warm water and assigned a score of 0 to 5 (Fig. 2.) by 2 trained observers. The same observers were present at each harvest date. The scores were later compared, and if the score differed, the greater of the 2 values was used for statistical analysis.

Statistical Analysis

Dietary concentrations of NDF and peNDF as well as the particle size distribution were analyzed using the MIXED procedure of SAS (SAS Inst. Inc, Cary, NC). The model included the effect of diet and the sample within diet was random. 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. Rumen scores were analyzed as categorical data using the GLIMMIX procedure of SAS and the model included the fixed effect of diet and the random effect of block. Pen was considered the experimental unit for all dependent variables except particle distribution, NDF, and peNDF. Treatment means were reported as least squares means ± standard error of the mean (SEM). Treatment differences were considered statistically significant when $P \leq 0.10$ and a tendency when $0.10 > P \leq 0.15$.

RESULTS & DISCUSSION

Physically Effective NDF

The NDF concentration was greatest for CS, intermediate for WD, and least for NR and CON (Table 2.1; $P < 0.01$). In a companion study (Chapter 2), samples of each ingredient used in the treatment diets were analyzed to determine the nutrient composition throughout the study. The average NDF concentrations reported for corn stalks, SFC, and WDGS were 75.8 (minimum = 69.9%; maximum = 83.0%), 8.8 (minimum = 7.4%; maximum = 10.1%), and 34.0% (minimum = 31.2%; maximum = 37.1%), respectively. Because corn stalks had a greater NDF concentration than other ingredients used in the diet formulation, the NDF concentration of CS was greater than

WD, NR, and CON, which contained lower proportions of corn stalks. The NDF concentration for WD was greater than CON because WD contained the same proportion of corn stalks, but fibrous WDGS replaced a portion of SFC in the diet. In contrast, NR contained 0% of DM as corn stalks and 19.0% WDGS, whereas CON contained 0% WDGS and 7.5% cornstalks. Therefore, the similar NDF concentration of NR compared to CON reflects the 2.5-fold greater inclusion of WDGS, which contain approximately 44.9% the NDF concentration of corn stalks.

The particle size distribution of the individual ingredients used in this study was not evaluated; however, these measurements have been previously reported by Gentry et al. (2016), Jennings et al. (2020), and Lockard et al. (2021) for several ingredients commonly used in feedlot cattle diets. In the present study, the proportion of particles captured on the 19.0 mm screen was greatest for CS, intermediate for WD and CON, and least for NR ($P < 0.01$). The pattern observed in the proportion of particles retained on the 19.0 mm screen was likely dictated by the inclusion rate of corn stalks, which are predominantly retained on the 19.0 mm screen (Jennings et al., 2020). The CS, WD, CON, and NR diets contained 14.75, 7.5, 7.5, and 0% corn stalks, respectively. Particles retained on the 8.0 mm screen were greatest for CS and CON, intermediate for WD, and least for NR ($P < 0.01$). These differences could be explained by the greater inclusion of SFC and/or corn stalks in CS and CON compared to WD and NR. Jennings et al. (2020) reported the greatest proportion of SFC particles were retained on the 8.0 mm screen. Despite greater SFC inclusion in CON, the similarity in CON and CS may be because a proportion of corn stalks are also retained on the 8.0-mm screen. Therefore, the proportion of particles retained on the 8.0 mm screen in CON and CS is likely similar because the 7.25% greater corn stalks inclusion in CS offsets differences in particle size despite the 9.7% greater inclusion of SFC in CON. In contrast, there was no difference ($P = 0.82$) in the proportion of particles retained on the 4.0 mm screen, but particles retained on the 1.18 mm screen were greatest for NR, intermediate for WD, and least for CS and CON ($P < 0.01$). The NR diet likely had the greatest proportion of particles retained on the 1.18 mm screen because of the greatest inclusion of WDGS that contains more small particles. Similarly, Spowart et al. (2022) reported that increasing the proportion of WDGS in the diet increased the proportion of particles captured on the 1.18 mm screen. There was no difference ($P = 0.16$) in the proportion of particles captured on the bottom pan of the PSPS (particles < 1.18 mm). The percentage of particles > 4.0 mm were greatest for CS followed by CON, WD, and NR ($P < 0.01$). In Gentry et al. (2016), the percentage of particles > 4.0 mm did not differ between treatments containing 5 vs. 10% corn stalks; however, Jennings et al. (2020) fed diets containing 5, 10, and 15% corn stalks and reported that particles > 4.0 mm were greater for 10 and 15% corn stalks inclusion compared to 5% corn stalks. However, in the study conducted by Jennings et al. (2020), the proportion of particles > 4.0 mm did not differ between diets containing 10 and 15% corn stalks. This suggests that more than a 5% difference in the inclusion rate of corn stalks is needed to detect differences in the proportion of particles > 4.0 mm and agrees with the results of the current study.

Although roughage comprises a small proportion of high concentrate feedlot diets, these ingredients are critical to maintenance of rumen function. Research suggests that the particle size distribution and peNDF concentration of traditional roughage sources plays an important role in rumination time and subsequent rumen buffering capacity (Yang and Beauchemin, 2006a; Gentry et al., 2016). In contrast, Spowart et al. (2022) suggested that when fibrous byproducts such as SB and WDGS are added to feedlot diets, the high NDF concentration of these ingredients may result in overestimation of peNDF. However, additional research is needed to determine the utility of peNDF in feedlot cattle diets that contain lower concentrations of traditional roughage sources and higher amounts of processed grains and fibrous byproducts.

In the current study, peNDF was greatest for CS, followed by CON, WD, and NR which contained 10.7, 8.9, 8.0, and 5.9% peNDF, respectively. The NR diet contained no corn stalks and the lowest peNDF. In contrast, CS contained twice the amount of corn stalks than WD and CON and had the greatest peNDF. Although both WD and CON contained 7.5% of DM as corn stalks, CON had greater peNDF than WD because a greater proportion of the diet remained above the 4.0 mm sieve. This is probably because of the small particle size (< 4.0 mm) of WDGS included in WD as well as the greater inclusion of SFC in CON (54.7 vs. 64.8% of DM as SFC for WD and CON, respectively) captured on sieves > 4.0 mm. Despite the larger proportion of particles > 4.0 mm, the CON diet had lower peNDF than CS. This is likely because it also contained one of the lowest NDF concentrations and the SFC included in the diet contributes to the portion of particles > 4.0 mm but does not have a high fiber concentration. The NDF concentration of NR and CON were similar (18.4 and 18.6%, respectively); however, the peNDF of CON was much greater (5.9 vs. 8.9% for NR and CON, respectively). Because the NDF concentration of both diets was the same, this difference is largely driven by the presence of 7.5% corn stalks (which has larger particle size) in CON and 0.0% corn stalks in NR.

In addition, NR included 19.0% WDGS and a smaller proportion of SFC, shifting particle distribution of the diet in favor of smaller particles.

These results suggest that although high in NDF concentration, replacing either SFC or a portion of both the SFC and corn stalks with corn milling byproducts decreases the peNDF of the diet. This contrasts with Spowart et al. (2022), who observed greater peNDF when fibrous byproducts such as SB and WDGS were used to replace a portion of SFC. In the study completed by Spowart et al. (2022), the authors suggest that the primary contributor to increased peNDF of diets containing greater proportions of fibrous byproducts and less SFC was an increase in NDF concentration. However, in the current study, replacing SFC or both a portion of corn stalks and SFC with WDGS either increased (WD) or did not influence (NR) NDF, but decreased peNDF because of the greater proportion of smaller particles in the diet. This illustrates that dietary peNDF is difficult to interpret in feedlot diets, as variation in the proportion of individual ingredients as well as the NDF concentration and particle distribution likely impacts the peNDF of the total diet.

Rumination

A diet × day interaction ($P < 0.01$) was observed for daily rumination minutes. No differences in rumination were observed before transition to the dietary treatments on d 22. However, on d 25 (cattle were consuming 50% of their treatment diet and 50% of the original CON diet), and d 93 CS had greater rumination than NR, but rumination of CON and WD did not differ from CS or NR. On d 26, rumination was greater for CS than WD and NR, but rumination of CON did not differ from any of the dietary treatments.

Rumination minutes on d 28, 45, and 53 were greater for CS than CON and NR, but did not differ between WD and CS, NR, or CON. On d 34, CS also had the greatest rumination followed by WD and NR, but rumination of CON did not differ from WD or NR. On d 31 and 44, CON did not differ from CS or WD, but CS had greater rumination than WD, followed by NR. Rumination minutes were greater for CS, CON, and WD than NR on d 27, 35, 40, 46, 49, 51, 52, 56 to 59, 63 to 65, 67 to 72, 74, 75, 77 to 81, 83, 84, 86 to 88, 94, 99, 100, 102, 103, and 105 to 107. On d 85, rumination was greater for WD than NR and CON, but CS did not differ from WD, NR, or CON. On d 89, 92, and 95, rumination was greater for CS and WD than NR but did not differ between CON and any of the other dietary treatments. Rumination was greatest for CS, intermediate for WD and CON, and least for NR on d 29, 30, 32, 33, 38, 39, 41, 47, 48, 50, 54, and 55. On d 36, 37, 42, 43, 60 to 62, 66, 73, 76, 82, 90, 91, 96 to 98, and 101 rumination was greatest for CS, intermediate for CON, and least for NR, similarly, WD had greater rumination than NR but did not differ from CS or CON. On d 104, rumination of cattle fed CS and WD was greater than CON and NR.

The differences observed in rumination patterns suggest that earlier in the feeding period rumination minutes were greatest for CS, intermediate for WD and CON, and least for NR, whereas late in the feeding period rumination was greater for CS, WD, and CON than NR. This indicates adaption in the amount of rumination over time occurs following a change in diet composition. Similar results were observed by Crawford et al. (2022), where cattle fed diets containing 32.0 vs 8.0% CS had greater rumination for only the first 28 d of a 56-d feeding period. Alternatively, rumination minutes of NR remained low for the entire feeding period. Overall daily rumination minutes were greatest for CS, intermediate for CON and WD, and least for NR (556, 485, 502 and 372 min/kg, respectively; $P < 0.01$). Jennings et al. (2021) reported rumination minutes increased from 298.2 to 362. 5 min/d when the corn stalks concentration of the diet was increased from 5 to 15%. This 10% increase in roughage concentration resulted in a 21.6% increase in rumination. In the present study, increasing roughage from 7.5 to 14.75% increased rumination by 14.6 % and conversely, decreasing roughage from 14.75% to 0% decreased rumination by 33.1%. Therefore, for every 1.0% of corn stalks added to the diet, there was a 2.2% increase in rumination minutes in the study conducted by Jennings et al. (2021) and in the present study, increasing the proportion of corn stalks by 1.0% increased rumination time by 2.0 to 2.2%. This suggests that changes in rumination could be primarily driven by the roughage concentration of the diet and not NDF or peNDF concentration. Roughage NDF (rNDF) describes the NDF contribution of traditional roughage sources in the diet and is calculated by multiplying the dietary roughage concentration by the NDF concentration of the roughage source. In the current study, rNDF was greatest for CS, intermediate for CON and WD, and least for NR (11.2, 5.7, 5.7 and 0.0%, respectively), which follows the same pattern observed for rumination.

Increasing the proportion of peNDF in the diet is believed to increase rumination time in both beef and dairy cattle (Beauchemin et al., 2003; Kononoff et al. 2003, Jennings et al., 2020). However, in the current study, although CON had greater peNDF than WD, rumination did not differ. Similar diets to CON and WD were fed in a study completed by Spowart et al. (2022) and no difference was reported for rumination minutes when adding WDGS to SFC-based finishing diets containing SB. Therefore, the results of Spowart et al. (2022) coupled with those observed in the current study suggest

WDGS has similar rumination influence compared to SFC. Conversely, in NR, both SFC and corn stalks were replaced by WDGS. Therefore, the decreased rumination observed in cattle consuming NR indicates that WDGS stimulates less rumination than corn stalks. Traditional roughage sources have a lower bulk density than corn milling byproducts, physically stimulate rumination and chewing activity, and decrease passage rate (Welch et al., 1982; Beauchemin et al., 2003; Weiss et al., 2017). Mertens et al. (1997) suggested that non-forage fiber sources, such as corn milling byproducts, might not stimulate rumination as much as roughage. However, cattle consuming the NR diet containing 0% corn stalks still ruminated for 372 min, which indicates that perhaps there is a minimum rumination threshold regardless of dietary composition.

Rumination can also be influenced by DMI, with greater DMI causing greater rumination (Welch and Smith, 1970; Bae et al., 1981). Dry matter intake can be increased by including corn milling byproducts in the diet (Spowart et al., 2022). However, based on the results observed for DMI reported in Chapter 2, inclusion of corn milling byproducts did not increase DMI in the present study. In contrast, DMI was greatest for CS, intermediate for WD and CON, and least for NR (9.2, 8.9, 8.9, and 8.1 kg for CS, WD, CON, and NR, respectively). Evaluating the rumination per kg of DMI is important to assess potential biological responses in rumination minutes on an intake equivalent basis. A diet × day interaction ($P < 0.01$) was observed for daily rumination per kg of DMI. On d 25, 26, 35, 44, 48, 49, 63, 82, 82, 84, 92, 96, 98, and 105, CS had greater rumination per kg of DMI than NR, and rumination of CON and WD did not differ from either CS or NR. On d 27, 46, 52, 53, 58, 61, 62, 64, 66, 68, 72, 73, 76, 77, 78, 80, 88 and 91 CS and WD had greater rumination per kg of DMI than NR, and CON did not differ from CS, WD, or NR Cattle consuming CS had greater rumination per kg of DMI than CON and NR on d 34, 36, 37, 38, 42, 43, 45, 50 and 54, but WD did not differ from any of the 3 dietary treatments. Rumination per kg of DMI for cattle consuming CON, CS, and WD were greater than NR on d 51, 55, 56, 57, 59, 60, 65, 67, 69, 70, 71, 74, 75, 79, 81, 90, 100, 101, 103, 106, and 107. In contrast, rumination of CS was greater than CON, WD, and NR on d 29, 30, 31, 32, 33, 39, 41, and 47. Cattle consuming CON had greater rumination per kg of DMI than NR on d 87 and 99. On d 85 and 102, rumination was greatest for WD, intermediate for CON, and least for NR, and greater for CS than NR. Lastly, CS had greater rumination per kg of DMI than CON on d 28. Overall, cattle consuming CON, CS, and WD had greater ($P < 0.01$) rumination per kg of DMI than those consuming NR (54.9, 61.1, 57.3, and 46.6 min/kg DMI for CON, CS, WD, and NR, respectively), which contained no roughage and greater concentrations of corn milling byproducts. When adjusted for differences in DMI, the rumination data suggests that eliminating roughage from the diet reduced rumination minutes, whereas increasing the proportion of NDF and peNDF from corn stalks or WDGS did not impact rumination. Additionally, the similar rumination per kg of DMI observed for CS, WD, and CON suggests that the greater DMI of CS was the primary driver for the greater total rumination minutes observed for cattle consuming this diet.

A diet × hour interaction ($P < 0.01$) was observed for rumination at 0200, 2200, and 2400 h, where CS had the greatest rumination, CON and WD were intermediate, and NR was least. Cattle consuming CS had greater rumination than WD and NR at 0400 h, whereas rumination of CON was greater than NR but did not differ from CS and WD. At 0600 WD and CS had the greatest rumination time, was intermediate for CON and was least for NR. Rumination for WD at 2000 h was not different from any other treatment, but CS had greater rumination than CON and NR. Rumination was greater for CON, CS, and WD than NR at 1200 h. At 1600 h rumination for CON did not differ from other treatments, but CS and WD had greater rumination than NR. At 1800 h rumination was greater for WD than CON, and CS and NR did not differ from the other treatments.

Similar to daily rumination, data for circadian rumination patterns indicate that removing the corn stalks from the diet decreased rumination minutes. Circadian rumination of feedlot cattle typically follows a pattern where rumination is least during and immediately after feeding (0600 to 1000 h) and near dusk (1600 to 2000 h), and greatest throughout the night up to the next feeding, when cattle have less activity (2400 to 0400 h; Stricklin and Kautz-Scanavy, 1984; Tomczak et al., 2019). In general, this pattern of rumination behavior is consistent with the results observed for cattle consuming CS, WD, and CON. However, rumination of cattle consuming NR followed a different pattern where rumination increased from 0800 to 1800 h (during daylight hours) relative to 2000 to 0600. This change in pattern is difficult to explain but could have occurred because of technological error. Because the cattle consuming NR had low rumination minutes, it is possible that the technology devices used to estimate rumination categorized activity during eating and other behaviors during daylight hours as an increase in overall rumination minutes. Additional research examining animal behavior of cattle consuming diets containing 0% roughage is needed to determine if the dietary roughage concentration impacts animal behavior patterns.

Ruminal pH

There was a treatment × day effect ($P < 0.01$) observed for ruminal pH. On d 14, cattle assigned to CS had greater ruminal pH than WD; however, this occurred when all cattle were consuming CON and is therefore likely a result of random variation and not biologically relevant. On d 29, ruminal pH was greatest for CS and CON, intermediate for WD, and least for NR. Ruminal pH was greatest for CS, intermediate for WD and CON, and least for NR on d 30 and 32. On d 42 ruminal pH was greatest for CON, intermediate for CS and NR, and least for WD.

However, minimal differences were observed in daily ruminal pH of cattle consuming diets with increasing fiber from corn stalks or WDGS over the entire feeding period, where average daily ruminal pH for CON, CS, WD and NR was 6.1, 6.1, 6.0 and 6.0 , respectively (effect of diet; $P = 0.78$) (When treatment effects occurred, they suggest that cattle consuming diets where at least a proportion of the diet included corn stalks had greater ruminal pH. Removing corn stalks from the diet appeared to impact ruminal pH most immediately after the transition to the respective treatment diets and administration of a terminal re-implant. Rapid changes in diet can decrease ruminal pH, particularly when transitioning from a high forage to a high concentrate diet (Holthausen et al., 2013). However, cattle in this study were transitioned over a 6-d period from one high concentrate diet to another with differing inclusion of the fiber source. Nevertheless, changes in dietary composition may alter eating behavior which can impact rumen environment by decreasing ruminal pH (Holthausen et al., 2013). Alternatively, it is possible that the stress imposed on cattle during administration of a terminal re-implant and withholding feed and water on d 0 influenced eating behavior and/or rumen fermentation patterns such that the greater concentration of roughage supplied by CS was needed to help modulate changes in pH that could have occurred following the re-implant administration and feeding delay.

Our hypothesis was that decreasing the starch concentration of the diet would increase ruminal pH. The average ruminal pH of cattle consuming CON, CS, WD, and NR were 6.1, 6.1, 6.0 and 6.0, respectively. Therefore, the current study indicates that average pH through the day was minimally impacted by diluting the starch concentration of the diet with either physically effective fiber from corn stalks or non-forage fiber sources such as WDGS. No difference in ruminal pH of cattle consuming diets containing increasing concentrations of WDGS agrees with research by Corrigan et al. (2009) and Luebbe et al. (2012). Corrigan et al. (2009) replaced 0 or 40% SFC with WDGS in a finishing diet and reported no difference in average daily ruminal pH. Similarly, Luebbe et al. (2012) replaced SFC with 15, 30, 45, or 60% WDGS and observed no difference in average daily ruminal pH. The results of the current study also imply that replacing a proportion of the SFC or both the SFC and corn stalks in the diet with 9.5 or 19.0% WDGS does not negatively impact ruminal pH. Research evaluating rumen fermentation patterns of cattle consuming traditional roughage sources vs. WDGS is limited and requires additional investigation.

Cattle consuming CS had greater rumination than CON, WD, and NR. Increasing the dietary roughage concentration has been observed to stimulate chewing and subsequent production of saliva, which acts as a buffer to rumen pH (Jiang et al., 2017). Because there was no difference in ruminal pH between CS and NR, this also suggests the greater rumination observed for CS did not influence the rumen environment. This disagrees with research conducted by Jennings et al. (2020) who reported mean ruminal pH of cattle consuming 15% corn stalks tended to be greater than those consuming a 5% corn stalks diet. However, when the concentration of corn stalks was only increased from 5 to 10%, no difference in ruminal pH was observed (Jennings et al., 2020). In the present study, corn stalks were increased by 7.25% and could explain why no difference in ruminal pH was observed as the changes in dietary roughage concentration and/or the decrease in dietary starch content may not have been large enough to detect differences in ruminal pH.

Increasing the proportion of corn stalks or WDGS resulted in 6.8, 6.6, and 5.7% reductions in the dietary starch concentration for CS, WD, and NR, respectively. In a study conducted by Spowart et al., (2022), reducing the dietary starch concentration by 6.8% from replacing SFC with 20% WDGS increased ruminal pH from 5.47 to 5.63. In contrast, reducing dietary starch by 4.8% from replacing SFC with 10% WDGS in diets containing 20% SB did not impact ruminal pH. When considered with the results of the current study, this implies that factors other than dietary starch concentration, roughage concentration, and peNDF influence ruminal pH.

In contrast to daily ruminal pH, evaluating changes in hourly ruminal pH may provide better insight into the effects of changes in dietary composition on ruminal pH as fermentation patterns fluctuate throughout the day based on diet and feeding behavior. There was a diet × hour interaction ($P < 0.01$) where NR had lower ruminal pH than CON at 0400 h. At 0600, CON had the greatest ruminal pH, CS was intermediate, and cattle consuming WD, and NR exhibited the lowest pH. Ruminal pH of cattle fed CON, and CS were greater than those fed WD and NR at 0800. The overall results of this study suggest that replacing roughage and processed grains with fibrous corn milling byproducts does not greatly impact daily or hourly ruminal pH. However, additional evaluation of changes in ruminal pH patterns, such as time spent below specific pH thresholds, could provide further understanding on the impacts of dietary changes such as replacing roughage with fibrous corn milling byproducts on the rumen environment.

Rumen Scores

The rumen score distribution of cattle consuming each dietary treatment is presented in Table 3.2. Cattle consuming CON had a greater ($P = 0.09$) percentage of rumen score 3 than CS, WD, or NR, however there was no difference ($P \geq 0.31$) among treatments in the proportion of cattle that received a rumen score of 0, 1, 2, 4, or 5. The rumen scoring system used was designed to evaluate differences in rumen health and integrity. Consumption of highly fermentable diets can result in high ruminal acid loads which reduce ruminal pH and challenge homeostasis of the ruminal epithelia (Penner et al., 2011). A critical component of the rumen are the papillae that protrude from the ruminal epithelium. These papillae serve to increase the absorptive surface area for VFA's (Steele et al., 2016), and when damaged can reduce absorptive capacity, negatively impact performance, and lead to secondary metabolic disorders, such as liver abscesses.

We hypothesized that decreasing the proportion of dietary starch would increase ruminal pH and reduce the occurrence of ruminal scarring and lesions. However, no difference was observed in rumen scores except for the proportion of CON rumens that received a score of 3. A rumen score of 3 describes the presence of multiple healed ulcerations, devoid of papillae, that make up a large portion of the rumen epithelium. Based on the rumen scores reported, it seems that increasing the roughage concentration in CS and removing roughage in NR did not clearly influence the physical characteristics of the rumen. However, visual appearance of the rumen alone may not provide sufficient information to fully evaluate the impacts of reducing starch and altering the dietary fiber source on rumen health and function. Jennings et al. (2021) reported increasing roughage from 5 to 15% of diet DM did not affect ruminal papillary morphology. However, the effects of completely removing roughage from the diet on rumen papillary morphology have not yet been evaluated in the current study and will provide valuable insight into the impact of physically effective roughage vs. non-forage fiber sources.

CONCLUSION

Inclusion of corn milling byproducts in feedlot diets provides protein and energy and has the potential to increase the NDF and peNDF concentration of the diet while simultaneously reducing starch concentration.. The results of this study agree with previous research suggesting that increasing peNDF in the diet increases rumination. Therefore, this study suggests that rumination is influenced by the physical characteristics of the fiber source. In contrast, because ruminal pH was not affected by diets that generated greater rumination time or had less starch, it suggests that small changes in ingredient inclusion and/or nutrient composition may not impact ruminal acidity. Most interestingly, these results indicate that roughage can be replaced entirely with fibrous corn milling byproducts without negatively impacting rumen pH. In addition, diet had minimal effect on visual rumen health; however, further analysis of papillary morphology and histology will allow a more complete conclusion on the effects of removing roughage from the diet on rumen health.

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Table 3.1. Ingredient composition and nutrient analysis of finishing diets including increased corn stalks, wet distillers grains with solubles, and no corn stalks.

	Treatments			
Item	CON	CS	WD	NR
Ingredient, % of DM				
Corn grain, flaked	64.8	55.1	54.7	54.2
Sweet Bran	20.0	20.0	20.0	20.0
WDGS	0.00	0.00	9.5	19.0
Corn Stalks	7.50	14.75	7.50	0.00
Corn Oil	1.10	3.52	1.75	0.22
Molasses Blend[1]	2.50	2.50	2.50	2.50
Supplement[2]	4.10	4.10	4.10	4.10
Nutrient Composition, DM basis[3]				
Dry Matter, %	78.1	78.7	70.3	63.6
NDF, %	18.6	22.6	21.2	18.4
rNDF, %[4]	5.7	11.2	5.7	0.0
ADF, %	8.5	12.2	10.2	7.5
Crude Protein, %	14.1	14.2	15.3	16.8
Crude Fat, %	4.6	6.5	5.6	4.8
Total Starch, %	50.4	43.6	43.8	44.7
ME, Mcal/kg[5]	3.07	3.07	3.08	3.10
NEm, Mcal/kg[5]	2.11	2.11	2.12	2.13
NEg, Mcal/kg[5]	1.45	1.44	1.45	1.47

[1]72 Brix Molasses Blend (Westway Feed Products LLC, Hereford, Texas).
[2]Formulated to meet or exceed NASEM requirements for vitamins and minerals (NASEM, 2016) and supplied 39.3 mg/kg monensin sodium and 9 mg/kg tylosin phosphate on a DM basis.
[3]Analyzed by Servi-Tech Laboratories (Hastings, NE).
[4]Roughage NDF = Corn stalks inclusion % × NDF % of corn stalks
[5]Formulated using tabular values (NRC, 2000).

Rumen Score	Description
0	No evidence of scar tissue and/or active lesions. Thick, lush papillae cover the entire ruminal epithelium and can be long and narrow or long and wide. Discoloration should be noted.
1	No evidence of scar tissue and/or active lesions. Papillae are not as thick or lush as a rumen score of 0 but cover the entire ruminal epithelium. Minor spots of consolidation (no papillae) and evidence of papillae hardening, clumping, and/or parakeratosis can be observed.
2	One scar/healed ulceration present with missing papillae, regardless of papillae color or length.
3	Multiple healed ulcerations devoid of papillae that make up a large portion of the rumen epithelium.
4	One active (open) rumenitis lesion devoid of papillae.
5	Multiple active (open) rumenitis lesions. Severe active rumenitis and ulcers devoid of papillae that make up a large portion of the rumen epithelium.

Table 3.2. Scoring system used to evaluate health and integrity of the ruminal epithelium.

Table 3.3. Particle separation and physically effective NDF (peNDF) of diets formulated with increased corn stalks, wet distillers grains with solubles, and no corn stalks.

	Treatments					
Item	CON	CS	WD	NR	SEM	*P*-Value
No. of Samples	26	26	26	26	-	-
NDF, % of DM	18.6[a]	22.6[b]	21.2[c]	18.4[a]	0.39	<0.01
Sieve Screen Size, mm	Retained / Screen, %					
19.0	0.63[a]	1.66[b]	0.67[a]	0.03[c]	0.14	<0.01
8.0	40.0[a]	37.8[a]	32.7[b]	29.7[c]	0.99	<0.01
4.0	21.2	20.9	20.7	20.7	0.42	0.82
1.18	24.4[c]	24.9[c]	30.5[b]	36.2[a]	0.56	<0.01
Bottom Pan	13.9	14.7	15.5	13.4	0.69	0.16
Particles > 4mm	61.8[a]	60.4[a]	54.0[b]	50.4[c]	1.03	<0.01
Est. peNDF 4mm, % of DM	8.9[b]	10.7[a]	8.0[c]	5.9[d]	0.21	<0.01

[1]Standard error of the mean.

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

[3]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 3.4. Ruminal pH and rumination minutes in proportion to DM intake of finishing beef cattle fed diets formulated with increased corn stalks, wet distillers grains with solubles, and no corn stalks.

	Treatments[1]					*P*-Value		
Item	CON	CS	WD	NR	SEM[2]	TRT	Day	TRT × Day
Daily ruminal pH	6.1	6.1	6.0	6.0	0.08	0.78	<0.01	<0.01
Daily Rumination, min/d	485[b]	556[a]	502[ab]	372[c]	23.86	<0.01	<0.01	<0.01
Rumination, min/kg DMI[3]	54.9[a]	61.1[a]	57.3[a]	46.6[b]	2.90	<0.01	<0.01	<0.01

[1] CON = control, 7.50% corn stalks and no wet distillers grain with solubles; CS = 14.75% corn stalks, no wet distillers grain with solubles; WD = 9.50% wet distillers grain with solubles; NR = no corn stalks and 19.00% wet distillers grain with solubles.

[2] Standard error of the mean.

[3] Calculated by dividing daily rumination minutes by daily nutrient intake of dry matter (DM).

Table 3.5. Rumen scores of cattle consuming diets formulated with increased corn stalks, wet distillers grains with solubles, and no corn stalks.

	Treatments[1]					
Item	CON	CS	WD	NR	SEM[2]	*P*-Value
Rumen Score, %						
0	8.4	2.4	6.3	9.0	2.69	0.31
1	50.6	55.3	64.5	56.0	6.47	0.36
2	18.7	17.8	13.3	19.7	4.45	0.62
3	15.3	7.9	5.0	5.0	3.31	0.09
4	4.1	10.5	5.9	4.7	3.01	0.35
5	3.0	6.0	5.1	5.6	2.78	0.80

[1]CON = control, 7.50% corn stalks and no wet distillers grain with solubles; CS = 14.75% corn stalks, no wet distillers grain with solubles; WD = 9.50% wet distillers grain with solubles; NR = no corn stalks and 19.00% wet distillers grain with solubles.
[2] Standard error of the mean.

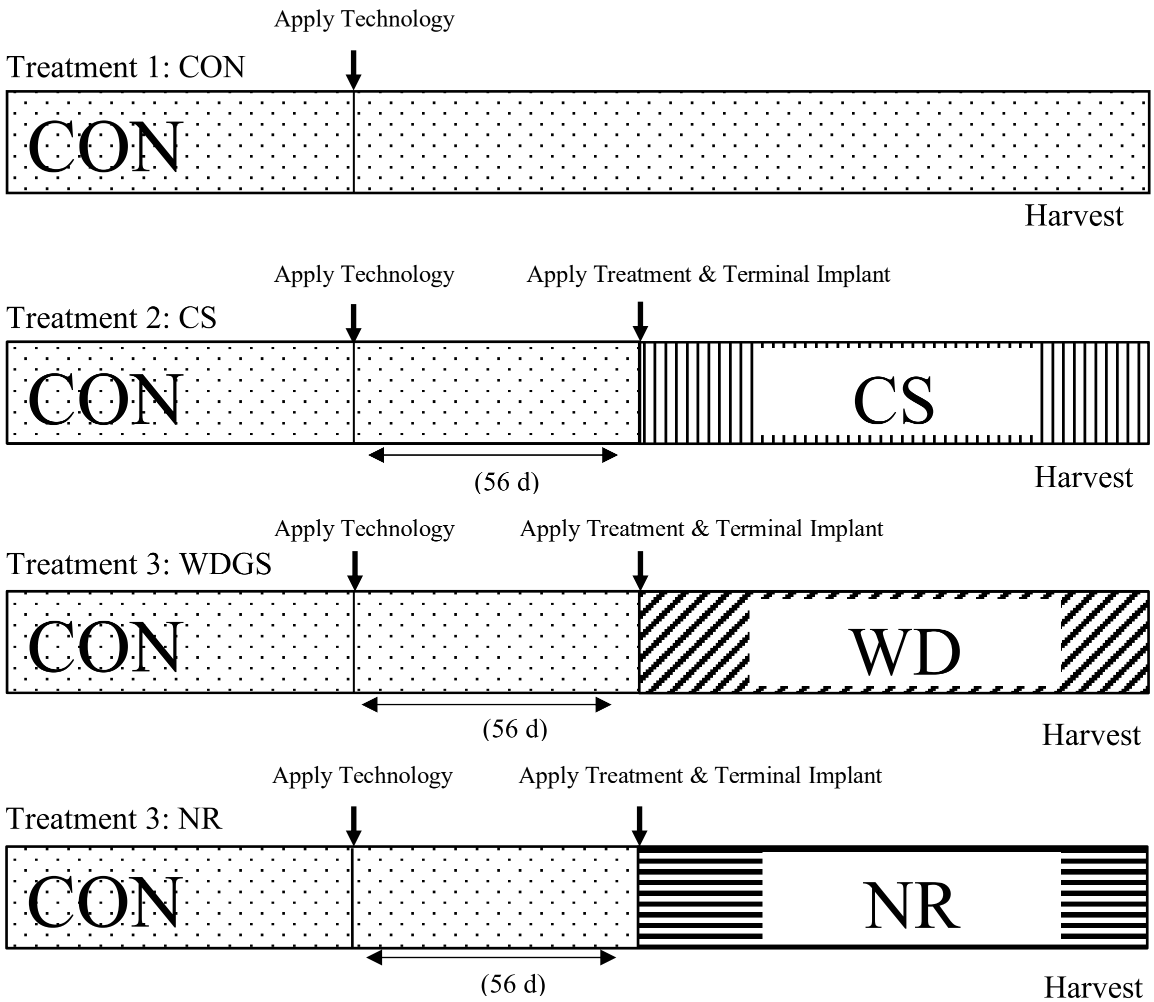

Figure 3.1. Administration of technology and application and timing containing sweet bran, corn stalks, wet distillers grain with solubles and no corn stalks in finishing cattle.

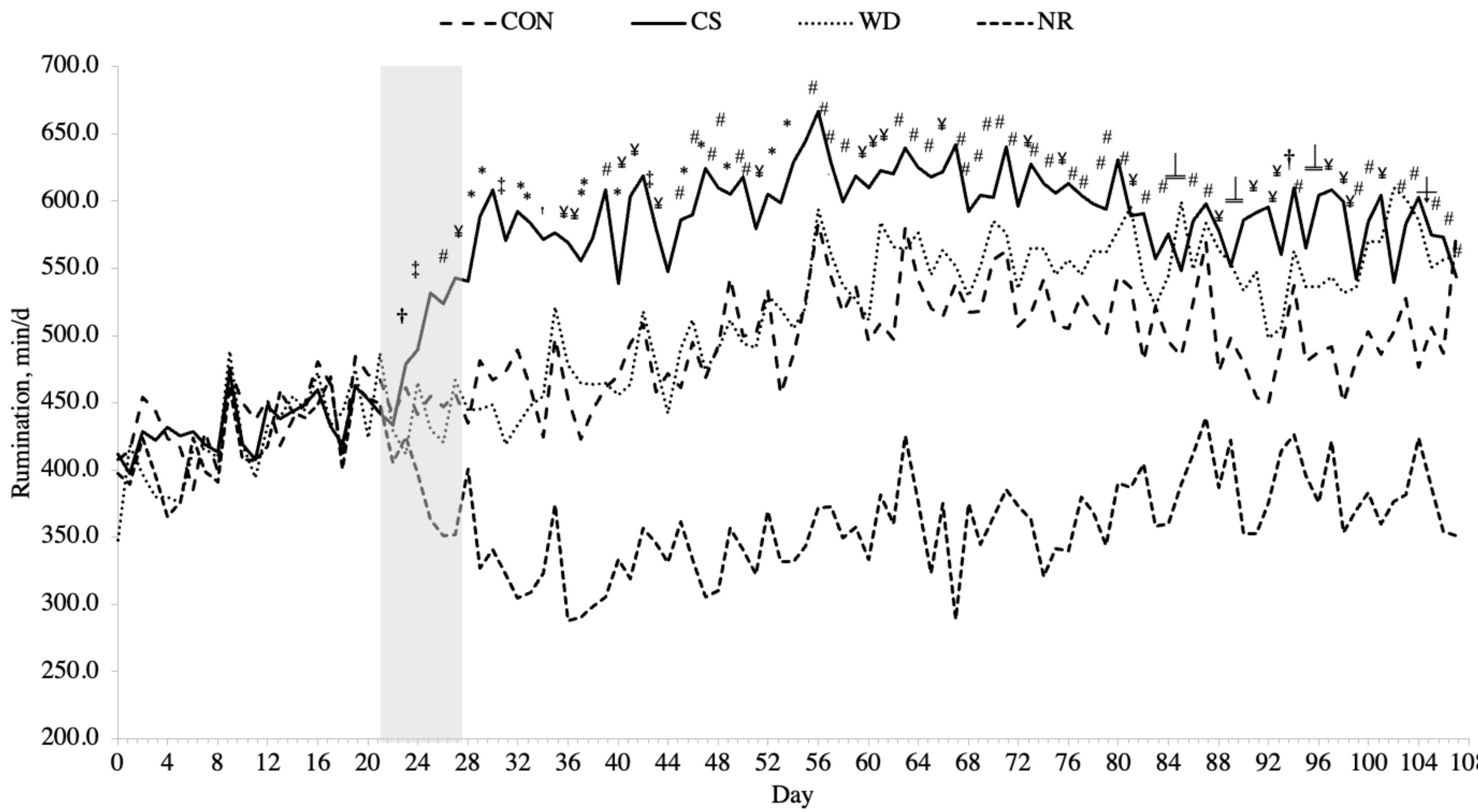

Figure 3.2. Daily rumination of finishing steers fed CON = control, 7.50% corn stalks and no wet distillers grain with solubles; CS = 14.75% corn stalks, no wet distillers grain with solubles; WD = 9.50% wet distillers grain with solubles; NR = no corn stalks and 19.00% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive a 3-axis accelerometer tag (Allflex Livestock Intelligence, Madison, WI) to quantify rumination minutes. D 0 to 21 = days before application of dietary treatment, all cattle consuming CON. D 22 to 28 (shaded) = transition to dietary treatments. D 29 to 107 = days on dietary treatment. Effect of diet, $P < 0.01$; day, $P < 0.01$; diet × day, $P < 0.01$. Pooled standard error of the mean = 23.86 min. *CS > CON and WD > NR; †CON and CS > NR; ‡ CON and CS > WD and NR; # CS, CON and WD > NR; ¥ CS > CON and NR; ┼ CS and WD > CON and NR; ˈ CS > CON, WD and NR; ┴ CS and WD > NR treatments differ within day, $P \leq 0.10$.

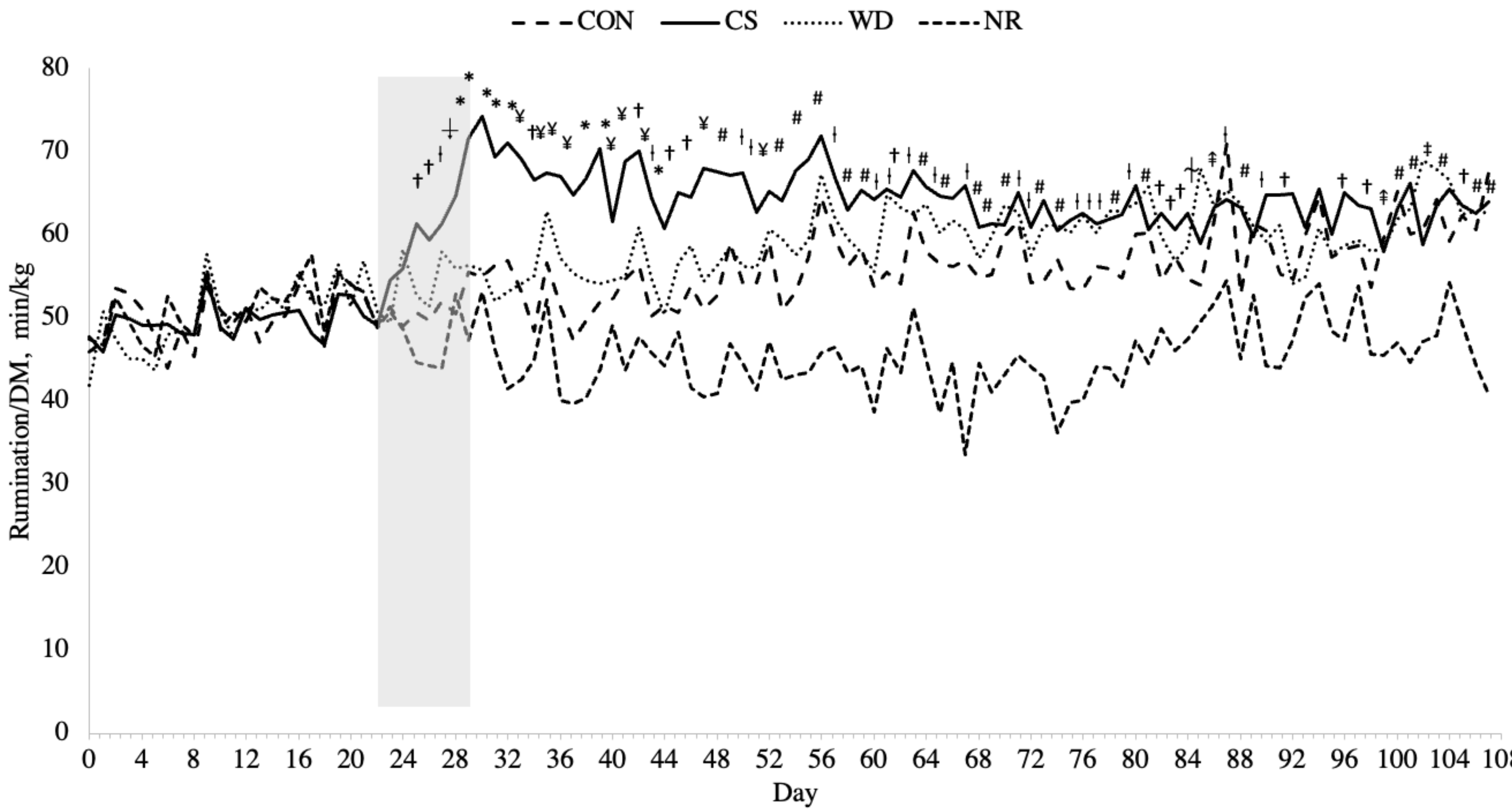

Figure 3.3. Daily rumination per kg of DM consumed by finishing steers fed CON = control, 7.50% corn stalks and no wet distillers grain with solubles; CS = 14.75% corn stalks, no wet distillers grain with solubles; WD = 9.50% wet distillers grain with solubles; NR = no corn stalks and 19.00% wet distillers 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 minutes. D 0 to 21 = days before application of dietary treatment, all cattle consuming CON. D 22 to 28 (shaded) = transition to dietary treatments. D 29 to 107 = days on dietary treatment. Effect of diet, $P = < 0.01$; day, $P < 0.01$; diet × day, $P < 0.01$. Pooled standard error of the mean = 4.74 min. *CS vs. CON, WD, NR; †CS vs. NR; ‡ CON and WD vs. NR; # CS, CON and WD vs. NR; ¥ CS vs. CON and NR; ┼ CS and WD vs. CON and NR; ┴ CS and WD vs. NR treatments differ within day, $P \leq 0.10$.

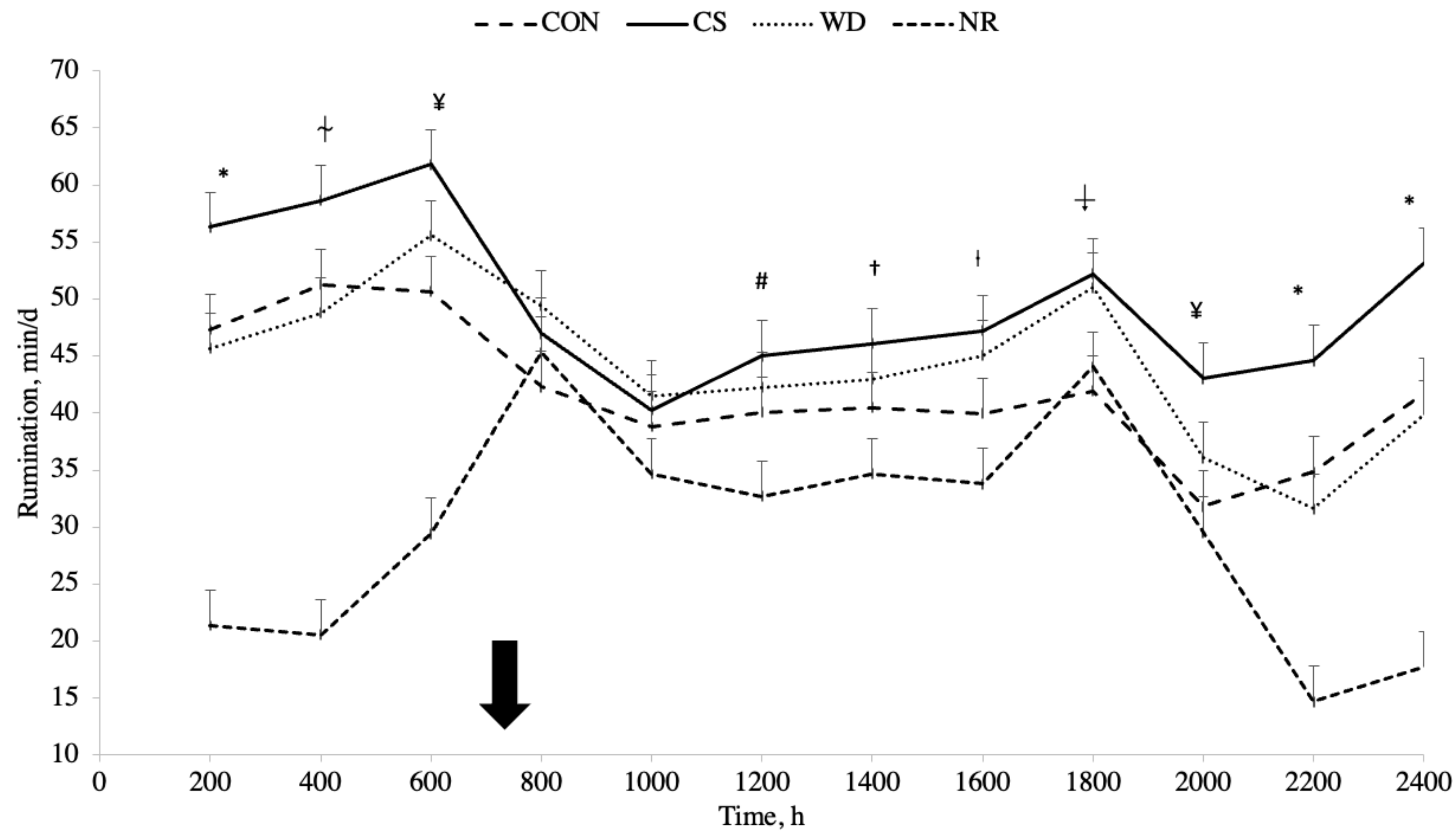

Figure 3.4. Overall (day 0 to final) circadian hourly rumination of finishing steers fed CON = control, 7.50% corn stalks and no wet distillers grain with solubles; CS = 14.75% corn stalks, no wet distillers grain with solubles; WD = 9.50% wet distillers grain with solubles; NR = no corn stalks and 19.00% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive a 3-axis accelerometer tag (Allfex 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. The arrow represents feeding beginning at 0730 h. Effect of diet, $P < 0.01$; hour, $P < 0.01$; diet × hour, $P < 0.01$. † CS > NR; # CS, CON and WD > NR; ¥ CS > CON and NR; * CS > CON, WD > NR; ⊥ WD > CON; ¦ CS and WD > NR; ∤ CS > WD and NR treatments differ within day, $P \leq 0.10$.

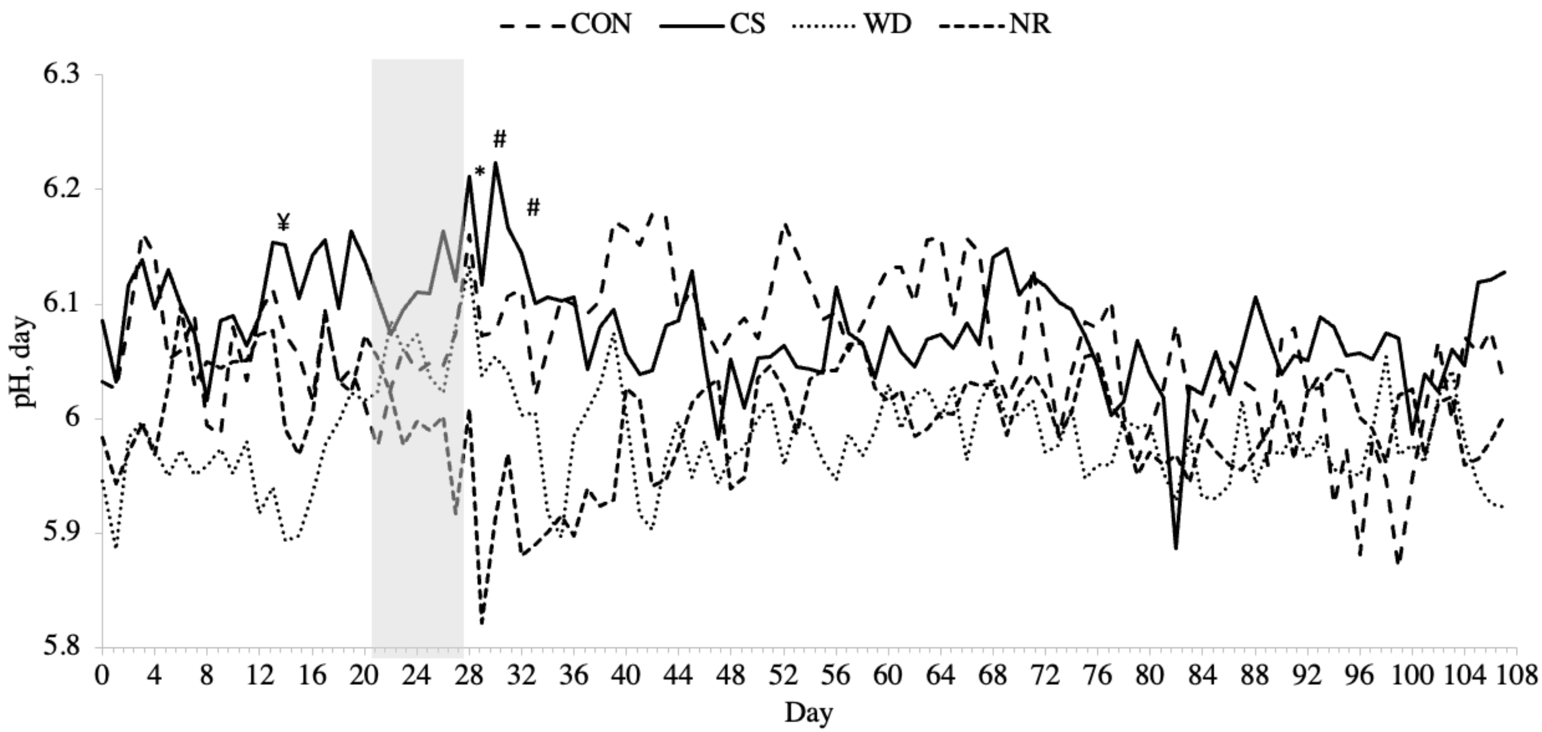

Figure 3.5. D 0 to final ruminal pH of finishing steers fed CON = control, 7.50% corn stalks and no wet distillers grain with solubles; CS = 14.75% corn stalks, no wet distillers grain with solubles; WD = 9.50% wet distillers grain with solubles; NR = no corn stalks and 19.00% wet distillers grain with solubles. Two steers from each pen were randomly selected to receive an indwelling ruminal pH bolus (SmaXtec, Graz, Austria) and ruminal pH data were automatically logged in 10-min time intervals. D 0 to 21 = days before application of dietary treatment, all cattle consuming CON. D 22 to 28 (shaded) = transition to dietary treatments. D 29 to 107 = days on dietary treatment. Effect of diet, $P = 0.78$; hour, $P < 0.01$; diet × hour, $P < 0.01$. *CON and CS > NR; †CON > WD; # CS > NR; ¥ CS > WD treatments differ within day, $P \leq 0.10$.

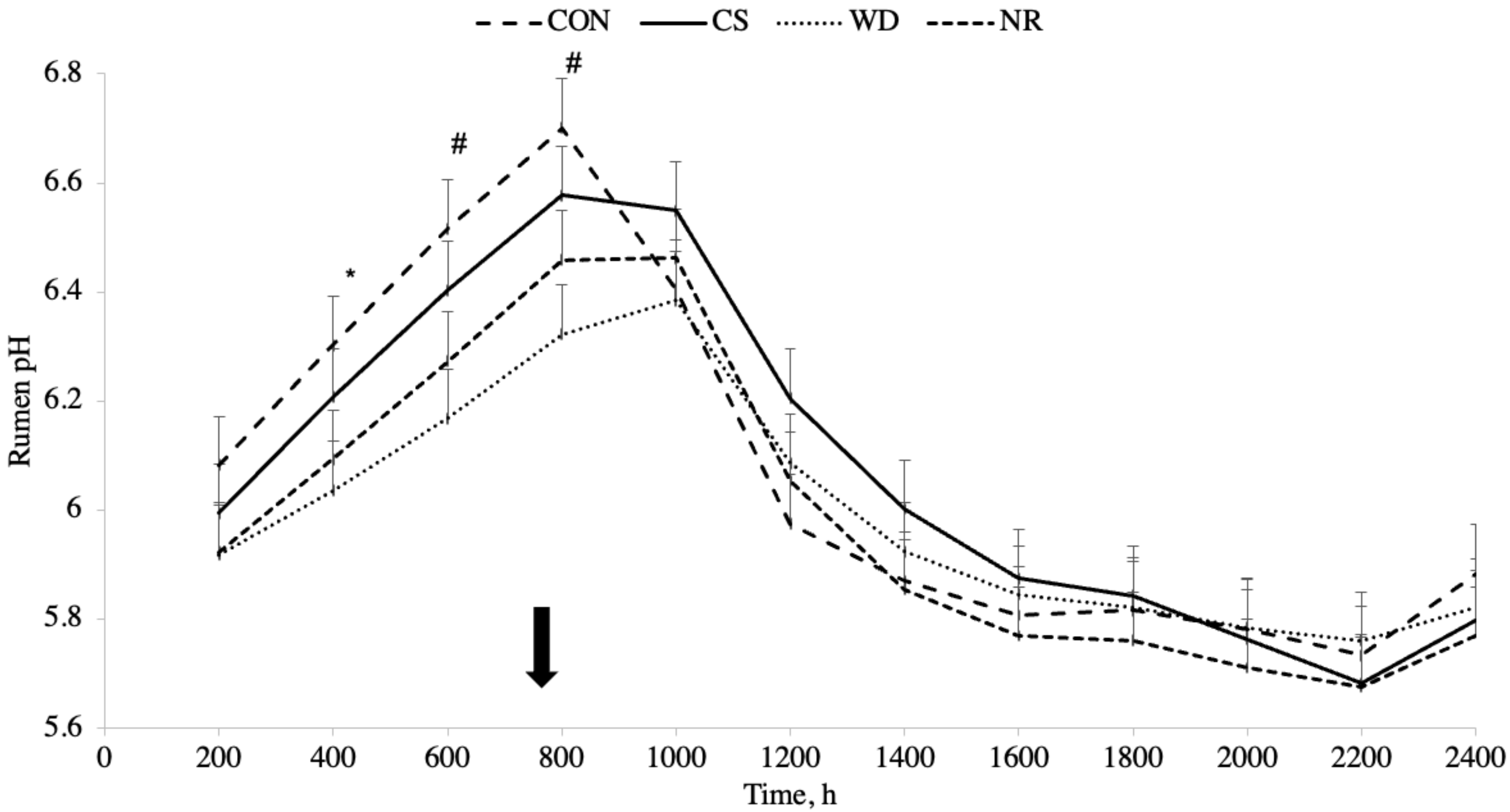

Figure 3.6. D 0 to final ruminal pH of finishing steers fed CON = control, 7.50% corn stalks and no wet distillers grain with solubles; CS = 14.75% corn stalks, no wet distillers grain with solubles; WD = 9.50% wet distillers grain with solubles; NR = no corn stalks and 19.00% wet distillers grain with solubles.. Two steers from each pen were randomly selected to receive an indwelling ruminal pH bolus (SmaXtec, Graz, Austria) and ruminal pH data were automatically logged in 10-min time intervals. Effect of diet, $P < 0.01$; hour, $P < 0.01$; diet × hour, $P < 0.01$. * CON > NR; # CON > WD and NR; ¥ CON and CS > WD and NR treatments differ within day, $P \leq 0.10$.