Evaluating the Addition of Water to a Barley-Based Finishing Diet on Feed Sorting Behaviour, Digestibility, Steer Performance, and Carcass Characteristics

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ABSTRACT

The objectives of the studies within this thesis were to evaluate the effects of adding water to a dry-rolled barley grain-based finishing diet on dry matter intake (**DMI**) and feed sorting behaviour. In Chapter 3, 8 ruminally cannulated beef steers (341.5 ± 25.1 kg starting body weight (**BW**)) were used in a study designed as a replicated 4 × 4 Latin square, with 21-d periods consisting of 16 d for diet adaptation and 5 d for data and sample collection. Chapter 4 utilized 120 beef steers (331.0 ± 31.0 kg starting BW) that were stratified by BW and randomly assigned to 1 of 20 pens (6 steers/pen, 5 pens/treatment) in a finishing growth performance study lasting 150 to 181 d. Dietary treatments for both studies included water at 0% (**CON**), 10% (**10W**), 20% (**20W**), and 30% (**30W**) relative to the barley grain weight. Both studies used barley-based finishing diets consisting of (dry matter (**DM**) basis) barley grain (88%), barley silage (7.7% in Chapter 3, 9.6% in Chapter 4), mineral and vitamin premix (4.1% in Chapter 3, 2.4% in Chapter 4), and titanium dioxide (0.2% in Chapter 3 only). The major difference between experiments was that Chapter 3 utilized aggressively processed barley grain with a processing index (**PI**) of 62.2 ±2.1% and 3.2 ±1.0% percent fines, whereas the barley grain in Chapter 4 had a PI of 84.2 ± 3.4% and 2.1 ± 1.0% percent fines. In Chapter 3, increasing water inclusion linearly increased DMI and water intake ($P < 0.01$ and $P = 0.04$, respectively). As water inclusion increased, the sorting index for the pan approached 100% ($P < 0.01$) indicating that steers consumed more fine particles. The increase in DMI and fine particle consumption led to linear decreases for mean ($P < 0.01$) and maximum ruminal pH ($P = 0.02$), and linear increases for the duration that ruminal pH was <5.5 ($P = 0.02$) and the ruminal lipopolysaccharide concentration ($P < 0.01$). In Chapter 4, DMI, average daily gain, and the gain:feed ratio were not affected by water inclusion ($P \geq 0.46$). Sorting index values for particles retained on the 19-, 4-, and 1.18-sieves, and the pan were quadratically affected by the addition of water ($P \leq 0.02$) such that the magnitude of the sorting decreased (values moved towards 100%) at a decreasing rate as water inclusion increased. Carcass characteristics (hot carcass weight, cold carcass weight, dressing percentage, and ribeye area) did not differ among treatments ($P \geq 0.15$). However, increasing water linearly reduced variability within a pen for marbling scores ($P = 0.05$). Collectively, these results are interpreted to suggest that adding water to a barley-based finishing diet may be an effective strategy to reduce feed sorting behaviour without altering digestibility, thereby reducing the variance for carcass marbling scores.

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LIST OF ABBREVIATIONS

10W	10% added water treatment
20W	20% added water treatment
30W	30% added water treatment
ADF	Acid detergent fiber treatment
ADG	Average daily gain
aNDFom	Ash-free neutral detergent fiber
BW	Body weight
Ca	Calcium
CBGA	Canadian Beef Grading Agency
CCW	Cold carcass weight
CDS	Condensed distillers solubles
CON	Control treatment
CP	Crude protein
CVAS	Cumberland Valley Analytical Services
DEXA	Dual energy x-ray absorptiometry
DM	Dry matter
DMI	Dry matter intake
DP	Dressing percentage
G:F	Gain to feed ratio
HCW	Hot carcass weight
KPH	Kidney, pelvic, and heart fat
LFA	Liquid feed additive
LPS	Lipopolysaccharide
NIRS	Near-infrared spectroscopy
NDF	Neutral detergent fiber
NE_g	Net energy for gain
NE_m	Net energy for maintenance
OM	Organic matter
P	Phosphorus
PI	Processing index
PSPS	Penn State Particle Separator
RCY	Retail cut yield
REA	Ribeye area
SCFA	Short chain fatty acid
SD	Standard deviation
SEM	Standard error of the means
TMR	Total mixed ration

1.0. GENERAL INTRODUCTION

Diets for finishing cattle typically include a high proportion of concentrates with a minimal forage inclusion, resulting in a dry, sortable diet. Given the high starch inclusion of these diets, feeding management is a critical factor influencing animal health and therefore, feedlot profitability. Various management strategies, such as increasing feeding frequency, manipulating the particle size of the total mixed ration (**TMR**), proper TMR mixing equipment and mixing times, and implementing slick-bunk management, have been utilized to achieve high and consistent average daily gain (ADG) while minimizing the incidence of digestive disorders. Despite these efforts, the actual eating behaviour of cattle often receives minor attention, and the sorting behaviour of finishing cattle is frequently overlooked. Sorting behaviour can occur for many reasons such as feed palatability, forage content, and particle size (Nombekela et al. 1994; Leonardi and Armentano 2003; Llonch et al. 2020). In fact, many feedlots operate under the assumption that because there is minimal feed remaining in the bunk, all cattle within a pen must have consumed the same diet. However, studies conducted with dairy cattle (Leonardi et al. 2005; Greter and DeVries 2011; Miller-Cushon and DeVries 2017b), and more recently in feedlots (Custodio et al. 2016; Dykier et al. 2019), have demonstrated that individual cattle do engage in sorting behaviour, that may result in the consumption of different dietary components even though the same diet was offered to all cattle.

In western Canada, barley grain serves as the primary energy source in finishing feedlot diets. Barley grain requires physical processing before feeding to break the fibrous hull and pericarp of the kernel, ensuring rumen microbes have access to the starch inside the kernel (Beauchemin et al. 1994b). However, barley kernel size can have dramatic differences depending on barley varieties (Bradshaw et al. 1996; Sýkorová et al. 2009), growing conditions (Weston et al. 1993), and agronomic practices (Edney et al. 2012). Additionally, many grain elevators will blend both light and heavy weight barley to create a more marketable mid-weight barley (Yang et al. 2013). Mixing of barley sources further amplifies the variability in kernel size and complicates dry-rolling of barley, making it difficult to achieve optimal processing on a single roller setting. With variable kernel size, larger kernels may be over processed, producing more fines due to kernel shattering, thereby reducing feed intake, and increasing the risk for digestive upset; whereas smaller kernels may pass through the rollers unprocessed resulting in kernels that

do not have the starch exposed, thus making them unavailable for microbial fermentation (Ahmad et al. 2010). To ensure that all the barley grain is accessible for ruminal digestion, feedlots may extensively process the barley. Extensive processing maximizes ruminal and total tract digestibility, but consequently also increases the incidence of ruminal acidosis, bloat, laminitis, and liver abscesses (Beauchemin et al. 2001).

A potential solution to minimize dietary sorting and maximize a consistent intake among pen-mates is to include a binder in the diet, such as liquid feed additives, to adhere dietary components together (DeVries and Gill 2012). However, the use of such additives depends on regional availability and the on-farm infrastructure required for storage and handling. A simpler, and more readily available, solution may be to include water in the TMR. While research has explored adding water to dairy rations (Leonardi et al. 2005; Felton and DeVries 2010; Fish and DeVries 2012), no studies to my knowledge have investigated this approach for feedlot diets. If feedlots can utilize water to prevent cattle from sorting these fines, this could enhance weight gain, reduce days on feed, and decrease carcass characteristic variability within pen mates, ultimately improving feedlot profitability.

2.0 LITERATURE REVIEW

2.1. Barley Grain

2.1.1. Barley grain production in Canada

Barley is a commonly grown cereal crop in Canada, valued for its versatility as both a grain and forage crop. In the year 2023, there was 8.896 million tonnes of barley harvested across Canada, which ranks fourth highest followed behind wheat, canola, and corn grown in the country (Statistics Canada 2023). Barley grain is classified according to its end use of either malt, feed, or food purposes, with the highest-quality malting barley meeting malting standards for the brewing industry (Canadian Grain Commission 2023). However, only approximately 20% of the seeded malting barley meets the criteria to be accepted as malting barley, leaving the other approximately 80% of the barley grain to be repurposed as feed barley (Canadian Grain Commission 2023). Additionally, forage varieties of barley are commonly grown to produce preserved greenfeed or silage for cattle feeding when harvested at an immature stage (Manitoba Agriculture 2006). In 2023, Alberta government reported that there were 627,300 tonnes of barley that was seeded for greenfeed and silage production, yielding 2.4 tonnes per acre for greenfeed and 6.3 tonnes for silage, which are historically low yields due to the drought conditions the prairies experienced (Government of Alberta 2024). However, it is important to note that there was a 43.7% increase in barley greenfeed and 13.5% increase in barley silage production in 2023 as the barley was salvaged and repurposed as an additional feed source for cattle due to the drought conditions (Government of Alberta 2024).

Numerous factors influence the quality of the harvested barley grain. For varieties to be registered, there must be consistent size and shape of the kernels. However, globally and regionally there are diverse growing conditions and agronomic practices that influence the characteristics of the barley grain that is harvested. Even within the same field, quality of the harvested kernels can vary due to topography and soil type changes. Environmental conditions have a critical role on the quality of the harvested barley. For example, low rainfall and high temperature (drought) growing conditions can cause a decrease in kernel size and bushel weight of the barley, which ultimately reduces the yield of the grain produced (Honsdorf et al. 2017). Drought conditions can also cause an increase in the protein content of the barley grain, which may exceed the standards for grain to be marketed as malting quality, discounting the grain, and

directing it into the feed industry (Weston et al. 1993). Altering agronomic practices such as seeding and fertilization rates, can also change the kernel size of the barley grain produced (Edney et al. 2012), which can further contribute to the kernel variability of the harvested grain.

There are many different barley varieties (Bradshaw et al. 1996) each with their own distinct traits, further contributing to the variability in kernel size of the produced grain. Barley is classified as either 2- or 6-row varieties and are either hulled or hulless varieties. Hulled barley varieties are the most common and these cultivars have a tightly fused husk and pericarp. Hulless varieties were developed with the hull loosely attached to the seed coat so that the hull is shed during harvest (Taketa et al. 2008). The major difference between 2- and 6-row barley is the arrangement of kernels within the head of the plant. As the name indicates, 2-row varieties have the grain aligned in two single rows providing the kernels with more space to grow, ultimately producing fewer, larger grain kernels. Conversely, 6-row varieties have more hexagon seed head shape, containing more kernels, but generally smaller kernels so the plant can support the seed head. Because of the ability for the kernels to grow larger, 2-row barley varieties typically have a higher starch content than 6-row varieties (Saleem et al. 2020). That said, there can be a large variation in kernel dimensions, contributing to variability for 6-row barley varieties. A study by Sýkorová et al. (2009) analyzed six different barley varieties and reported that within a cultivar there was up to a 4.90 mm length, 1.60 mm width, and 1.68 mm height differences from the largest kernel to the smallest kernel within the samples they collected. Although these differences may be small, when calculating the difference among all varieties evaluated in the study of Sýkorová et al. (2009) would increase variability to 6.84 mm length, 2.11 mm width, and 2.11 mm height differences from the largest to the smallest kernels.

Grain elevators receive many loads of barley from various regions and producers, some of the barley being of excellent quality with a heavy bushel weight and some barley that is of poorer quality and has a lighter bushel weight. The bushel weight is measure of the density of the kernels within a given volume (500 mL), where a heavy bushel weight indicates that the seeds are a higher quality (Grains Canada, 2024). Often, grain elevators will blend both light and heavy-weight barley to produce a more marketable mid-weight barley, targeting 618 g/L, further amplifying the variability in kernel size within each load (Yang et al. 2013). This mid-weight

barley is marketed and sold for livestock feed, where the variable kernel size complicates grain processing procedures.

Aside from bushel weight, chemical composition of the grain is also considered when marketing barley. The main difference between barley achieving malting standards or going into the feed market is the protein level. Malting barley must have a protein content between 11 and 12.5% to adequately take up water and have proper enzyme activity to break down the starch (North Dakota State University 2008; Alberta Grains 2024). Protein concentrations lower than 11% disqualify the barley from malting and redirect it to the feed market, where protein contents higher than 12.5% can direct the barley into a different process producing malt for distilling if all the other requirements for malting are achieved including germination, moisture content, kernel plumpness, and being free of disease or other damage (Alberta Grains 2024). Otherwise, this barley is also directed into the feed market.

2.1.2. Structure of barley grain

Barley grain requires processing before feeding to cattle to optimize digestibility. The barley grain kernel is composed of five distinct layers (Figure 1): the husk, pericarp, testa, aleurone, and endosperm (Arendt and Zannini 2013). The husk, also known as the hull, forms the tough outermost layer of the barley kernel and is highly resistant to digestion. The pericarp and the testa are fused to form the seed coat layer, which is extremely important for keeping moisture out of the kernel to preserve the quality of the kernel. The only time moisture penetrates the seed coat is during germination for the seed to grow. The fibrous nature of the hull and pericarp require damage for the rumen microbes to access the starch within the kernel (Beauchemin et al. 1994b). Chewing alone does not sufficiently damage the seed coat for starch accessibility due to the hard nature of the kernels, and therefore, mechanical processing is required (Yang et al. 2000). Within the seed coat, the aleurone layer is a protein layer that encases the endosperm. The endosperm contains starch granules consisting of amylose and amylopectin. The starchy endosperm is the largest part of the kernel and is the primary reason that barley grain is fed to ruminants, providing a highly fermentable starch content for its high-energy properties.

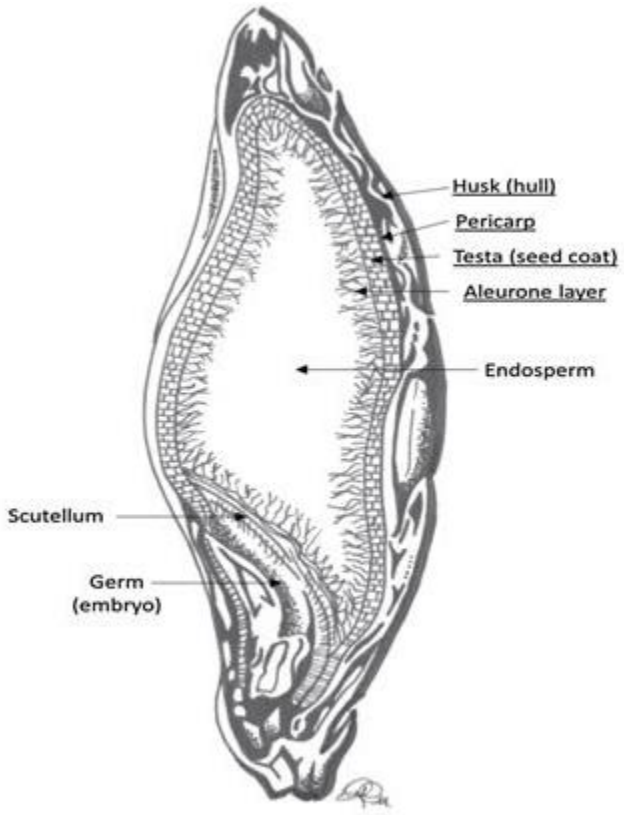

Figure 1.1. Cross-section of a barley kernel showing each layer, from Arendt and Zannini (2013).

2.1.3. Variable kernel size processing techniques

The variability in barley kernel size complicates mechanical processing, as a single roller setting may not adequately process all kernels within a batch. With variable kernel sizes, larger kernels may be over-processed, leading to kernel shattering as they pass through the rollers and consequently producing more fine particles. Over-processing elevates the likelihood of digestive upset and ruminal acidosis due to the rapid fermentation rates for these fine particles (Owens et al. 1997; Koenig et al. 2003). Conversely, when under-processed, the seed coat of kernels is not sufficiently damaged leaving little opportunity for fermentation or mammalian digestion processes. As a consequence, much of the starch may pass through the gastro-intestinal tract and is excreted in the manure (Ahmad et al. 2010). The DM digestibility of whole barley is, on average, 16% less than processed barley, with starch digestibility decreasing by 37% (Mathison 1996). As such, under-processed kernels are excreted in the feces, resulting in increased fecal starch loss (Koenig and Beauchemin 2011a), rendering an economically undesirable situation for feedlots due to the high cost of barley grain.

2.2. Methods of assessing processing adequacy for dry-rolled barley

Tools have been developed to assess the adequacy of kernel processing, aiming to determine if kernels are sufficiently damaged for maximum starch digestion without causing digestive upset due to fine particle production. Common methods to process barley grain and mitigate the variability in kernel size while maximizing digestibility include dry-rolling, grinding, temper-rolling, and steam-flaking.

2.2.1. Physical characteristics

Processing index (**PI**) is a common calculation-based method used to determine processing adequacy for dry-rolled grain. Processing index is calculated as the volume weight (kg/L) of the grain after processing in a standardized 500-mL container (using a cox funnel) when expressed as a percentage of the original unprocessed grain weight in that same volume (Yang et al. 2000). Methodology for ensuring the container is full without the sample being compressed follows that of Canadian Grain Commission (2024). As processing severity increases, the volume weight of the processed sample decreases, indicating the generation of more fines and lighter material. Thus, a lower PI value reflects more aggressive grain processing.

The advantages of this method are that there is an instant result, it requires inexpensive equipment, and it can be completed on-farm. However, a disadvantage to this method is the requirement for the original unprocessed grain. Often, acquiring the original sample can be difficult in a commercial mill or a large feedlot that processes a large quantity daily. Moreover, this measurement must be made frequently as the incoming grain and processed grain can vary in density within a bin.

For barley grain processing, feedlots may target a wide range of PI values, typically ranging from 65 to 80% depending on the specific operation (Jancewicz et al. 2017b). A study by Ran et al. (2021) investigated three PI values of 65, 75, and 85%, and determined that 75% PI was optimum when dry-rolling barley for digestibility since decreasing the PI to 65% did not improve digestibility but increasing to 85% reduced digestibility. Although there were no major differences reported between the 65 and 75% PI, 75% was more economical because it could be processed faster and should generate fewer fine particles reducing the risk for digestive upsets. However, the PI method only accounts for the change in volume weight and may not be sensitive enough to provide an indication for the proportion of fine particles that may be present.

Percent fines are another method that can be used to determine processing severity. Percent fines are measured by sieving a 1-L volume of processed barley through the Penn State Particle Separator (**PSPS**) using the 1.18-mm sieve and the pan. Fines are classified as particles that pass through the 1.18-mm sieve and are collected in the pan. The percent fines can be calculated by dividing the weight of the sample collected in the pan by the weight of the original sample and is expressed as a percentage. Typically, more aggressive barley processing results in a higher percentage of fines. This is also a method that provides an instant result, is fast and repeatable, and if the operation already has a PSPS there is no additional equipment needed. However, this method alone does not determine processing adequacy and may provide a skewed result if the original whole grain sample is contaminated with fine particles (e.g. weed seeds and dust) that may also pass through the 1.18-mm sieve. For dry-rolled barley, it is recommended that percent fines are 3% or less to maximize starch digestibility without generating excessive fines that may increase risk for digestive upset (Mathison et al. 1997). However, in recent years, higher levels of percentage fines, approaching 5%, have been tolerated.

The PI and the percent fines methods should be used together simultaneously. In a practical application, a feedlot processing grain should first do a PI to determine the severity of the grain processing and then adjust the roller mill to achieve the desired PI percentage. Then, a sample should be evaluated to determine the percent fines, and if fines are higher than 3 to 5%, the processing severity should be decreased. This procedure should be completed frequently, with a minimum frequency for every new load of grain received, since variability of the grain between loads is likely to be different and the roller mill will need to be adjusted accordingly.

2.2.2. Fecal starch

Fecal starch serves as another strategy to evaluate barley grain processing adequacy. Fecal starch is starch that escapes digestion and is excreted in the feces, acting as an indicator of total tract starch digestion (Zinn et al. 2002; Corona et al. 2005). Assessing fecal starch offers a relatively straightforward method for evaluating processing adequacy, as fecal samples are collected at the pen level for analysis by wet chemistry or near-infrared spectroscopy (**NIRS**). However, by the time fecal samples are collected and analyzed, it is too late to change processing adequacy and the losses in production have already occurred. It should also be recognized that starch in silage can also contribute to the fecal starch concentration (Johnson et al., 2020).

Fecal starch values should be as low as possible, with larger values often indicating that processing is not aggressive enough to allow microbes access to the starchy endosperm of the grain kernel (Ferraretto 2023). However, it is unlikely to obtain values <1% as microbial glycogen can be detected as starch with the current methodology used to evaluate fecal starch. Jancewicz et al. (2017a) collected fecal samples from feedlots in western Canada and reported an average fecal starch concentration of 7%. But fecal starch concentrations ranged from <1% to >25%. Fecal starch concentrations are from total tract digestion of the entire diet, and therefore, recovered starch may not only be from the barley grain. Starch from other sources, such as silage or greenfeed, may escape digestion and result in a higher fecal starch concentration. Johnson et al. (2020) observed that steers fed barley silage and rolled corn had whole barley kernels in the feces. Given that barley was only provided as part of the silage, other ingredients that provide starch may also contribute to the starch excreted in feces, particularly for silage.

Nixdorff et al. (2020) reported that total tract digestibility for starch ranged from 93.6 to 99.5%, with fecal starch ranging from 2.4% to 17.9% depending on barley grain processing method and severity. In recent years, calibrations have been completed to predict fecal starch using NIRS as a cost-effective and efficient means of predicting fecal starch and total tract starch digestion (Fredin et al. 2014; Jancewicz et al. 2017b). Multivariate regression was used in the development of the calibrations for NIRS (Jancewicz et al. 2017a) resulting in good prediction accuracy. Additionally, a correlation between fecal starch and performance has been identified, specifically for predicting ADG and the gain to feed ratio (**G:F**), as higher fecal starch concentrations correlate with lower performance due to starch escaping digestion and not be utilized by the animal (Jancewicz et al. 2017a).

2.3. Methods of processing barley grain

2.3.1. Dry-rolling

Dry-rolling is a processing technique where the whole dry grain kernels pass through two steel rollers spinning in opposite directions, aiming to break the kernel into two to three pieces. The inflow rate of the grain and adjustable gap width between the rollers determine the extent of processing, with slower inflow and narrower gap resulting in more extensive processing (Beef Cattle Research Council 2020). Rollers may be offset to prevent material from becoming caught and ensure a continual feed of the grain into the mill. Additionally, the rollers may rotate at the same speed (compression) or have rollers rotating at different speeds (shear) that help to further process the grain (Koch 2002). The rollers may be either smooth or grooved surfaces, significantly influencing the processing severity; smooth rollers compress the grain, while grooved rollers grind or tear the kernel (Koch 2002). Grooves are characterized by both their depth and the number of grooves per centimeter. A single-stage roller mill with 4 to 5 grooves per cm has been recommended for processing barley (Bauer et al. 2017).

Processing variable kernel size barley by dry-rolling presents challenges. The uniformity of the processed product directly correlates with the uniformity of the kernels being processed. Greater variability in the barley grain results in increased variability in the resulting rolled grain (Yang et al. 2013). Achieving adequate processing with a single roller setting is very difficult;

large kernels may shatter, producing fines, while small kernels may pass through the rollers untouched, leading to their excretion in the feces (Ahmad et al. 2010).

Dry-rolling barley is a common processing technique for feedlots. It offers a relatively low cost and provides flexibility regarding the amount that can be processed at once. Feedlots have the option to process a large quantity and store it for later use, or to process daily or for each load during feed-out to minimize the need for extensive storage space. Studies have compared dry-rolled barley to feeding whole barley. Toland (1976) found that dry-rolled barley exhibited an organic matter digestibility of 85.2%, whereas whole barley was only 52.5% digestible, with 48.2% of the whole barley being recovered in the feces. Mathison (1996) also noted a similar response, with starch digestibility improving by up to 37% for dry-rolled barley compared to whole barley grain. Additionally, Goonewardene et al. (1998) compared the growth performance of steers provided with either whole barley or dry-rolled barley through both the backgrounding and finishing phases. They concluded that steers consuming rolled barley had a 19.6% improvement in ADG during the backgrounding phase and a 0.8% improvement in the finishing phase compared to those fed whole barley, which may be due to an improvement in digestibility and utilization of the barley grain during the backgrounding phase. This previous research has supported the need for appropriate processing and monitoring of the processed barley, and research in recent years has investigated fecal starch concentrations along with methodology to evaluate adequacy of barley grain processing (Jancewicz et al. 2017b; Nixdorff et al. 2020).

2.3.2. Grinding

Grinding grain involves a processing method where a series of hammers in a hammermill physically grind or beat the grain until the particles pass through a screen (4-mm openings are common). Alternatively, a disc-mill can be used where the grain is crushed between a spinning disk and a screen. The size of the ground particles is regulated by the openings in the screen and the speed at which the hammers swing or disk spins (Koch 2002). Depending on the screen size, this process results in very few whole kernels passing through the screen. Like dry-rolling, grinding grain offers flexibility in how much product can be processed at one time, providing an option to process a large quantity at one time for use later. However, the hammers may pulverize the kernel to a fine consistency to enable passage through the screen, generating a less uniform

particle size distribution and a floury product with high levels of fines and dust. These fines pose a particular concern for digestive upset (Beauchemin et al. 2001), while the dust may reduce feed intake (Mathison 1996). Additionally, a comparison by Nielsen and Ingvartsen (2000) determined that dry-rolling resulted in a more uniform product than grinding, which contained a larger amount of fine particles. Grinding is an ideal processing method for grains intended for pelleting, as the fines can be recombined into a solid feed particle that resists sorting.

The recommendation for feeding ground barley grain varies for dairy and feedlot cattle. Dairy cattle can safely be fed ground grain due to the low inclusion rate and high forage content of their diet. A study by Sadri et al. (2007) compared dry-rolled, steam-flaked, and ground barley fed to mid-lactation Holstein cows and did not observe a difference on milk yield, milk composition, DMI, or ruminal pH. Conversely, grinding barley grain for feedlot cattle is not recommended due to the excessive production of fine particles and the large proportion barley makes up in the diet. Mathison (1996) reported that steers fed ground barley in a finishing diet had poorer feed efficiency (0.9% reduction), reduced feed intake (5% lower), and less back fat (0.15 cm less) than steers fed dry-rolled barley. This reduction is likely due to an increased onset of ruminal acidosis resulting from the elevated presence of rapidly degradable fine particles (Koenig et al. 2003).

2.3.3. Temper-rolling

Temper-rolling, often referred to as “tempering”, involves adding water to the cereal grain to increase its moisture concentration to approximately 18 to 20%. The grain is then steeped for 12 to 24 h to soften the seed coat prior to processing in a roller mill. This process restores moisture to the kernel, causing it to swell, thereby reducing kernel shattering and subsequent fine production during rolling (Yang et al. 2011; Nixdorff et al. 2020). Saponin-based surfactants may be added during tempering as a technique to improve the uptake of water into the barley kernel, as well as promoting the growth of starch-degrading rumen bacteria, thus, improving animal performance (Wang et al. 2003). Temper-rolling has gained popularity among feedlots as it thought to facilitate more consistent processing and to reduce the production of fine particles (Mathison et al. 1997). Beauchemin et al. (2001) recommended an optimum PI of 75% for finishing cattle but indicated that processing severity could be increased to 65% for feedlot diets containing adequate concentrations of effective fiber. However, tempering is associated

with high labour and infrastructure costs, and tempering in freezing conditions may not be feasible when operating outside without proper heating. Additionally, due to the moisture content of the product, grain must be processed regularly as storage, under aerobic conditions, is limited with the wet product and spoilage is likely to occur.

While tempering grain has been widely adopted by western Canadian feedlots (Mathison et al. 1997), its effects on animal performance have been inconsistent. Mathison et al. (1997) compared temper-rolled barley with dry-rolled barley at different PI for beef bull calves and reported no advantage to tempering barley prior to feeding, though there was an efficiency improvement with an increased processing severity with both processing methods. Conversely, Wang et al. (2003) conducted a similar experiment with beef steers and observed that tempering increased ADG, DMI, and G:F when compared to dry-rolled barley. More recently, Nixdorff et al. (2020) compared temper-rolled and dry-rolled barley that was fed to beef steers and found no difference for DMI, ADG, or G:F when the barley grain was processed to the same severity. These inconsistencies in results may be attributed to variation in steeping time affecting moisture absorption by the kernel and processing severity of the grain after steeping (Wang et al. 2003; Nixdorff et al. 2020). Nevertheless, tempering may allow for more aggressive processing of barley than dry rolling as the softened kernels flatten through the roller mill and do not shatter.

2.3.4. Steam-flaking

Another processing method that utilizes moisture is steam-flaking. Steam-flaking barley involves passing grain through a steam chest at 95 to 98°C for 5 min at atmospheric pressure (Johnson et al. 2020; Nixdorff et al. 2020) to increase the grain moisture to 18 to 20%, followed by rolling while the kernels and rollers are hot (Theurer et al. 1999). Similar to dry-rolling, the settings of the roller and feeding rate of the barley determine the processing severity, and variable-sized kernels may alter the consistency of the resulting flaked product, but processing severity can be more aggressive, as the kernels flatten rather than shatter. High-pressured steam disrupts the intramolecular bonds within the protein and starch matrix, particularly crucial for corn grain where the protein and starch matrix are tightly bound together (Zinn et al. 2002). Effects of steam have less impact on availability of starch in barley grain (Johnson et al. 2020; Nixdorff et al. 2020). Several feedlots have installed steam-flaking infrastructure primarily for processing corn but also intend on using this system as their only means of processing all grains

brought on farm. However, similar to tempering, the high moisture and temperature associated with steam-flaked grain necessitates frequent production to avoid spoilage.

Unlike corn grain, barley grain does not possess a tight protein and starch matrix. Owens et al. (1997) concluded in a review that compared dry-rolled and steam-flaked barley and found that steam-flaked barley result in greater feed efficiency depending on the flaking density. Nixdorff et al. (2020) compared dry-rolled, temper-rolled, and steam-flaked barley, using two different flaking densities. The authors reported that steam-flaked barley improved feed efficiency and starch digestibility compared to the other treatments. However, this improvement was associated with a decrease in ADG and hot carcass weight of the steers fed the finely-flaked barley; although this may not be a consistent outcome as the dry-rolled barley was under-processed (Nixdorff et al. 2020). While steam-flaking may not be economically feasible for processing barley grain alone due to the high infrastructure costs, it remains a viable option for feedlots seeking flexibility in processing different cereal grains.

2.4. Eating behaviour of feedlot cattle

2.4.1. Feedlot diets and feeding management

Feedlot diets are formulated to deliver a high amount of readily fermentable carbohydrates for digestion. In western Canada, feedlot diets typically incorporate a significant proportion of barley grain with minimal roughage inclusion (≤10% diet DM) to optimize weight gain, reduce days on feed, and enhance feed efficiency (Koenig and Beauchemin 2011a). Ensuring that grain is adequately processed is crucial to maximize starch digestibility in the rumen and total tract. As described in section 2.3.1, processing barley can be difficult due to the variable kernel size of the barley, and a large proportion of fine particles may be generated. Reduced DMI is a common response observed in cattle consuming a diet with a high proportion of fine particles. This reduction in intake may stem from diet dustiness or the onset of digestive and metabolic disorders including bloat, ruminal acidosis, laminitis, rumenitis, and liver abscesses (Mathison 1996; Owens et al. 1997; Beauchemin et al. 2001). Therefore, achieving an optimal balance between processing severity to maximize starch digestibility while minimizing the production of fine particles is essential for maintaining cattle health and optimizing performance in feedlot settings.

2.4.2. Bloat

Bloat is the most prevalent digestive disorder in finishing cattle (Wang et al. 2023). It can be classified into two types: free-gas bloat and frothy bloat. Free-gas bloat occurs when the normal production of gasses within the rumen cannot be eructated through the esophagus and accumulates in the rumen (Cheng et al. 1998; Wang et al. 2023). The inability for the gas to escape may result from an esophageal obstruction, damage to the vagus nerve due to pneumonia, or impaired ruminal motility from rapid ruminal acidosis onset (Cheng et al. 1998).

Frothy bloat is the predominant type of bloat in feedlot cattle, accounting for 90% of bloat cases (Cheng et al. 1998). It arises from the formation of a stable foam trapping gas produced during fermentation (Wang et al. 2012). In pasture settings, frothy bloat often correlates with a highly digestible, high-protein forage (such as alfalfa) that rapidly generates gas along with fine plant particles forming foam that traps the gas (Howarth et al. 1986). In feedlots, frothy bloat is associated with the proliferation of *Streptococcus bovis* in the rumen, resulting in high levels of lactate and capsular polysaccharide (slime) (Herrera et al. 2009; Wang et al. 2023). Additionally, frothy bloat is linked to ruminal acidosis, where a low pH is also observed which may further stabilize the foam (Cheng et al. 1998; Majak et al. 2003). Feeding a high-concentrate diet can cause the foam to expand, filling the rumen, and impairing nerve endings that control the opening of the esophagus preventing the eructation of the gas (Wang et al. 2023).

Particle size of the diet is also associated with frothy bloat. Wang et al. (2023) observed that increased fine particles available for fermentation accelerated lactic acid and bacterial polysaccharide production. Cheng et al. (1998) noted that as the processed grain particle size decreases and more starch becomes rapidly fermentable, there is an increased production of mucopolysaccharides, increasing ruminal fluid viscosity, and contributing to foam formation. The most effective mitigation strategy to reduce frothy bloat is transitioning cattle gradually from a forage to a high-grain diet slowly, allowing rumen microbes to adapt to the highly fermentable diet (Cheng et al. 1998), and avoiding the consumption of a large proportion of fine particles.

2.4.3. Ruminal acidosis

Ruminal acidosis is a fermentation disorder characterized extended durations of low ruminal pH, due to an imbalance between microbial production and absorption of short chain

fatty acids (**SCFA**; Castillo et al. 2012). The risk of ruminal acidosis increases when a high proportion of rapidly fermentable non-structural carbohydrates, particularly starch, is fed in feedlot diets (Owens et al. 1998). Microbes break down the starch into monosaccharides, rapidly fermenting them into SCFA. When a large amount of highly processed starch is consumed, this fermentation occurs rapidly, resulting in an excess of SCFA production. The imbalance between SCFA production and removal, through absorption, neutralization, and passage, leads to SCFA accumulation causing ruminal pH to decline and the resulting ruminal acidosis (Penner et al. 2007, 2009).

Cattle possess behavioural and physiological mechanisms to regulate ruminal pH. Behaviourally, cattle alter their feed consumption including the amount feed consumed, feeding patterns, and dietary sorting. These alterations in feeding behaviour control the supply of fermentable carbohydrates into the rumen and provides buffer to the rumen from saliva and rumen bicarbonate production (Penner et al. 2009). Similar to bloat prevention, the best mitigation strategy to prevent ruminal acidosis is diet formulation to manage ruminally fermentable starch and severity of cereal grain processing.

During low ruminal pH episodes, cattle modify their eating behaviour by reducing DMI and sorting their diet to selectively consume longer particles to prevent a further pH decrease and stimulate chewing for bicarbonate production (DeVries et al. 2008). A study by Marchesini et al. (2013) evaluated feeding dairy heifers starch levels of 17.3, 33.4, and 42.8% DM. The group fed the highest starch content exhibited the lowest ruminal pH and lowest DMI of all the treatments, suggesting a behavioural adaptation to reduce feed intake to avoid further pH reductions. Interestingly, heifers initially on the medium starch diet, which had already experienced a pH decline, further reduced DMI when switched to the high starch diet, indicating a learned behaviour to avoid repeating low pH symptoms that they had already experienced, and therefore had less severe ruminal acidosis than the first group. DeVries et al. (2008) compared dairy cows identified as either low or high-risk for ruminal acidosis based on dietary components and found that during severe ruminal acidosis, high-risk cows increased sorting for longer particles and sorted against shorter particles, aiming to increase physically effective fiber intake and reduce starch content to prevent further ruminal pH decrease and potentially stimulate bicarbonate production from increased rumen motility and rumination (DeVries et al. 2008).

2.4.4. Rumenitis, laminitis and liver abscesses

Severe ruminal acidosis poses a significant health and welfare concern for feedlot cattle. During ruminal acidosis, the acidic ruminal pH leads to the death and lysis of gram-negative bacteria, increasing free lipopolysaccharide (**LPS**) concentrations in the rumen (Khafipour et al. 2011). Rumen LPS, along with other bacterial products may cross the ruminal epithelium into the portal circulation, travel to the liver, and contribute to other disorders such as rumenitis, laminitis, and liver abscesses (Plaizier et al. 2012).

Rumenitis manifests as damage to the ruminal epithelium (Penner et al. 2011) and, while not commonly evaluated, it is prevalent in feedlot cattle when they are placed on high concentrate rations (Thomson 1967). There are no external clinical signs of rumenitis and there is debate for whether it should simply be considered as an adaptational response of the epithelium when there is a high production of acid and limited effective fiber intake. A definitive diagnosis of rumenitis can only be completed on ruminally cannulated cattle or post-mortem as evaluation of the ruminal papillae is required. Once papillae are damaged or eroded, nutrient absorption capacity decreases, exacerbating the risk and severity of ruminal acidosis (Penner et al. 2011). A study by Luna-Méndez et al. (2020) analyzed the rumens of cattle at a slaughter plant and found 98% of cattle had at least one site of rumen damage including hemorrhages, ulcers, papillae atrophy, and scarring. Their findings aligned with another study by Rezac et al. (2014) where the most common symptom of rumenitis was a decrease in the rumen papillae and scarring, indicating that the longer the exposure to an unfavourable environment, the more damage that is likely to occur (Luna-Méndez et al. 2020). When the rumen epithelium is extensively damaged, the barrier function of the tissue is compromised, and bacteria and toxins (such as LPS) can pass through the compromised tight junctions into blood circulation and disperse around the body (Penner et al. 2011).

Laminitis arises due to inflammation of the laminar corium of the hoof wall (Bergsten 2003), and typically occurs towards the end of the feeding period. The current theory on laminitis occurrence in feedlot cattle is that ruminal acidosis-induced damage to the ruminal epithelium from low ruminal pH allows endotoxins to pass into the bloodstream, affecting digital microvasculature hemodynamics (Nocek 1997). The vascular dysfunction leads to lameness due to endotoxins (such as LPS) and histamine that originate from bacterial lysis causing

vasoconstriction of the veins and dilation of the capillaries, resulting in an increase in blood pressure and seepage through the vessel walls resulting in edema, which thereby results in a reduction of oxygen and blood supply to the hooves (Nocek 1997). This causes degeneration of the dermo-epidermal junction in the laminar region of the hoof, harming its structural integrity (Ossent and Lischer 1998). A study by Danscher et al. (2009) was able to induce ruminal acidosis with an oral drench of oligofructose and the heifers responded with clinical signs of acute laminitis, determined by a combination of evaluating locomotion scores, hoof-testing, and joint distension, confirming the link between low ruminal pH and systemic effects to the hooves.

Similar to laminitis, when bacteria enter into the portal bloodstream, they can colonize the liver, causing liver abscesses. A liver abscess is a pus-filled capsule that is embedded within the lobes of the liver and can range in severity of size and number amongst animals (Nagaraja and Chengappa 1998). Cattle with liver abscesses often do not display clinical signs, but the abscesses are discovered at slaughter (Foreman 2023). The prevalence of liver abscesses in North American feedlot cattle range from 12 to 32%, thus resulting in a major economic impact for feedlots and slaughter plants (Brink et al. 1990). In Canada, the economic losses from condemned and discounted livers are estimated at $60 million annually (Beef Cattle Research Council 2016). Although clinical symptoms may not be obvious, production losses associated with liver abscesses include reductions in DMI, ADG, G:F, live weight, hot carcass weight, carcass yield, and subcutaneous fat deposition (Lawrence 2020).

2.5. Feed sorting behaviour

Cattle exhibit feed sorting to select feeds based on factors such as palatability, forage content, nutrient concentration, and particle size (Nombekela et al. 1994; Leonardi and Armentano 2003; Rosser et al. 2016; Llonch et al. 2020). This behaviour leads to changes in nutrient intake relative to that expected based on the diet composition and alters the nutritional value of the remaining feed in the bunk throughout the day (DeVries et al. 2005; Rosser et al. 2016). Feed sorting is often quantified using the sorting index, where the actual intake of each fraction on the PSPS is expressed as a percentage of the predicted intake (Leonardi and Armentano 2003). Values above 100% indicate selective consumption, below 100% indicate selective avoidance, and those not different from 100% indicate no sorting occurred. Most research on feed sorting has been conducted with dairy cattle, and observations suggest that dairy

cows typically sort against long forage particles and select concentrate components within the diet (Leonardi and Armentano 2003; DeVries et al. 2005; Miller-Cushon and DeVries 2009). However, DeVries et al. (2008) observed that dairy cows experiencing ruminal acidosis may select for long particles within the TMR to alleviate low ruminal pH. In addition, some authors have applied the sorting index calculation to evaluate nutrient sorting. Rosser et al. (2016) fed a high forage diet of whole-crop oat or whole-crop barley to beef heifers and found that heifers provided an immature crop sorted against the starch for the barley treatment only and did not sort the acid detergent fiber (**ADF**) content for both forage sources. As the crops advanced in maturity, the heifers sorted against the ADF in both sources of forage and sorted for starch for the oat treatment only. Pursley et al. (2020) observed a similar response that when beef heifers were fed a high forage diet, they also sorted against neutral detergent fiber (**NDF**) and sorted for crude protein.

In feedlot diets with a high proportion of grain and low forage inclusion, the dry and easily sortable nature poses challenges. Feedlot cattle sorting may lead to inconsistent growth and variable risk for digestive upset among pen-mates. Many feedlots in North America may overlook feed sorting issues as they impose ‘slick bunk’ feeding management and provide multiple feedings daily (Pritchard and Bruns 2003). However, this assumption overlooks hierarchical dynamics and nutritional requirements among pen-mates, as dominant animals may sort first, leaving the remaining feed for lower ranking animals. Schwartzkopf-Genswein et al. (2011) determined that higher gaining steers within a pen are at the feed bunk for a longer duration but make less trips to the bunk than lower gaining steers. It can be deduced that when cattle are at the feed bunk for a longer duration, they are likely spending more time sorting their feed. In feedlots, cattle may sort the TMR for longer particles to counter low ruminal pH resulting from rapidly fermentable grains in the diet (Yang and Beauchemin 2006; DeVries et al. 2014). DeVries et al. (2014) observed that cattle fed high-grain diets for extended periods learned to sort for longer particles to mitigate ruminal acidosis.

2.5.1. Strategies to reduce feed sorting behaviour

Various strategies can be implemented to discourage sorting of diets, including altering the DM concentration, controlling feed particle size distribution, and frequent feeding and feed push-up (Miller-Cushon and DeVries 2017b). In dairies, cows tend to sort against large particles

and for concentrate components (Leonardi and Armentano 2003; Leonardi et al. 2005; Fish and DeVries 2012); whereas feedlot cattle often exhibit the opposite behaviour, sorting for larger particles and against small and fine particles. Dykier et al. (2019) determined that feedlot steers sorted the diet to consume a different diet composition than what was offered, and that steers preferred larger particles. Interestingly, they found that even though the steers were consuming a different diet than what was offered, there were no differences in intake energy or digestible energy, but they did find that steers that were consuming a larger amount of 4- to 8-mm sized fraction had a poorer ADG.

Strategies used in dairies to minimize sorting and enhance forage intake can be adapted for feedlots. One common approach adopted in the dairy industry is adding moisture to the TMR to reduce its DM content. The rationale behind this approach is that the moisture addition helps bind small and large particles together, reducing the ability of cows to sort the diet and promoting consumption of the formulated diet (Leonardi et al. 2005; Denißen et al. 2021). Various moisture sources, such as water and liquid feed additives, can be incorporated into the TMR to serve as feed binders.

2.5.1.1. Water

The addition of water to feedlot diets presents a promising approach based on existing research findings. Water is a cost-effective and readily available binder, and studies in dairies have shown positive outcomes from its use. For instance, Lahr et al. (1983) investigated adding water to achieve 77.7, 65.0, 52.7, or 39.7% dietary DM and found that DMI decreased as the TMR DM content decreased and milk fat percentage increased as the DM content decreased. Similarly, Leonardi et al. (2005) observed reduced sorting against long particles, increased NDF intake, and increased milk fat percentage with increasing water addition to the TMR. These findings are relevant to feedlot diets, since the DM changed from 80.8 to 64.4%, which is dry for a dairy TMR, but a very common DM for feedlot diets. Another study by Fish and DeVries (2012) confirmed that adding water to a dairy TMR to change the DM from 61.7 to 51.9% reduced the ability of cows to sort for the small particles in the diet but those authors did not observe a change in production parameters for the cows.

Some studies have reported conflicting results regarding the effects of water addition on feed sorting behaviour. Miller-Cushon and DeVries (2009) also added water to a dairy TMR to reduce the DM content from 58 to 48% and found that increased water content in the TMR led to heightened sorting behaviour and reduced DMI, NDF intake, starch intake, without affecting milk production, suggesting a more filling effect in the rumen. Similarly, Felton and DeVries (2010) compared DM concentrations of 60, 54, and 48% and observed increased sorting with higher moisture concentration in the diet and reduced DM, NDF, and starch intake. This study however, recorded feed temperature and discovered that as the wetter diets sat out in the warm barn conditions (24.4 ± 3.3°C), the feed began to heat and was likely unpalatable encouraging diet sorting (Felton and DeVries 2010). Despite increased sorting, these two studies reported that milk production remained unaffected, indicating the digestibility improvements might offset the decrease in DMI.

Water addition to feedlot diets could yield positive outcomes, especially considering the difference in DM content and environmental conditions. First, diets do not need to be as wet as the diets previously tested for dairy cattle that reduced DMI (Leonardi et al. 2005; Fish and DeVries 2012). Second, most western Canadian feedlots have their finishing phase in the winter months and therefore may avoid spoilage effects that occur with wetter diets in the warmer months. However, the optimal water inclusion to maximize particle binding, while minimizing additional weight in the feed trucks, and to optimize the time it takes to add the water into the mixture is not known. Overall, incorporating water as a binder in feedlot diets has the potential to improve nutrient utilization and mitigate sorting-related challenges, ultimately enhancing animal performance and welfare.

2.5.1.2. Liquid feed additives

Liquid feed additives (**LFA**) such as molasses, vinasse, condensed distillers solubles (**CDS**), and whey offer alternative approaches to minimize dietary sorting while providing additional nutrients such as sugar, protein, minerals, and vitamins. These additives act as moisture sources enhancing the binding properties of the diet and potentially improving palatability (DeVries and Gill 2012). The downfall to including LFA in the diet is the increased cost, having adequate storage space for the product, the capability to handle the product appropriately, and the regional availability of the product.

Feed-grade molasses found in Canada is a by-product remaining from the table sugar industry using sugar beets. Molasses is classified as an energy-dense feedstuff due to the high content of easily fermentable sugars remaining within the syrup after the initial sugar extraction (Mordenti et al. 2021). Molasses can be a versatile LFA because of its sticky properties offering biding capabilities to reduce sorting of the diet and may act as a palatability enhancer due to its sweet taste (DeVries and Gill 2012). Industry adoption of molasses has come from anecdotal evidence as very little research has been completed to investigate the binding properties. One study by Eastridge et al. (2011) investigated molasses, as a sugar source, as an alternative to starch in the diet with a DM content of 64.7%. They reported that there was no effect of adding the molasses for DMI or the sorting of the diet (Eastridge et al. 2011). Another study by DeVries and Gill (2012) specifically looked at the dietary binding properties of molasses added to the TMR with a DM content of 51.1% and found that the molasses reduced the ability of cows to sort against the large particles, increased their DMI, and produced more milk with a higher fat percentage. In beef cow-calf production systems, molasses is often added to high-straw diets to encourage the consumption of dry and unpalatable feeds (Manitoba Agriculture 2018; Havekes et al. 2020). A study by Havekes et al. (2020) investigated molasses as a feed supplement on high-straw diets and reported that molasses addition reduced the ability of cows to sort the diet and promoted a more consistent intake of nutrients. These studies confirm that molasses can be a valuable feed additive to encourage intake and reduce dietary sorting in a range of diets provided.

Condensed distillers solubles are a by-product from the production of ethanol from cereal grains. After the distillation of the alcohol or ethanol, the remaining mash is centrifuged, where the resulting liquid is the thin stillage and may be dried slightly to create the CDS (De Boever et al. 2016). Condensed distillers solubles have the same syrup-like consistency as molasses discussed above and are a good source of energy, protein, and vitamins (Weiss et al. 2008). Often the CDS are incorporated back into the wet distiller's grains creating the commonly fed wet distillers' grains with solubles. However, some dairies and feedlots include CDS in the TMR to increase palatability, decrease dustiness, bind ingredients together, and reduce dietary sorting (Schingoethe et al. 2009). Although research has been completed on feeding CDS and the response for dairy cattle, no studies have specifically analyzed how adding CDS alters feed

sorting behaviour. It can be hypothesized that sorting outcomes would be similar to those with molasses, as both products have similar consistency and properties.

Whey is a byproduct of the cheese making process. Whey contains a high concentration of lactose making it an energy-dense LFA (Oba 2011). There are many types of whey products that can be fed including liquid whey, whey permeates, and dried whey; all with similar effects on ruminal fermentation (Oba 2011). Liquid whey only contains 7% solids, so it is more similar to water than molasses and CDS as described above (Anderson et al. 1974). Whey permeate has been marketed as binding liquid that reduces ration sorting and minimizes dust in the TMR (KW Alternative Feeds n.d.). Extensive research has been conducted using whey in the diets as a sugar source and its effect on ruminal fermentation and milk production (Oba 2011; Ravelo et al. 2022), but none of the studies have evaluated the dietary sorting behaviours of the cows when adding liquid whey to the TMR.

Overall, LFA present valuable options for enhancing nutrient utilization, reducing sorting behavior, and improving overall performance in cattle. Further research is warranted to fully understand the mechanisms underlying their effects on feed sorting and to optimize their inclusion in TMR formulations for various production systems

2.5.2. Management factors to reduce feed sorting behaviour

Aside from adding liquid binders to the diet, there are management factors that farms can incorporate to reduce sorting potential of the diet and to minimize variation in the consumed diet. These strategies include altering the feeding frequency and changing the particle size of the diet provided (Shaver 2002).

Feeding frequency refers to the number of times the TMR is delivered throughout the day. Changing the feeding frequency can be an effective strategy to reduce feed sorting and promote more consistent nutrient intake among cattle. The number of times fresh feed is provided per day has been shown to influence feed sorting, where providing the TMR more than once per day reduced feed sorting (Miller-Cushon and DeVries 2017b). DeVries et al. (2005) investigated the impact of changing feeding frequency for dairy cattle from once per day to twice per day and observed a reduction in sorting of the TMR with the more frequent feed delivery. Similarly, Hart et al. (2014) compared feeding frequencies of once per day to three times per day

and found that cows fed three times per day did not exhibit significant sorting behaviours based on sorting index calculations. By providing fresh TMR multiple times per day, cattle have more opportunities to consume a uniform diet, reducing the likelihood of selective consumption. This approach helps ensure that all animals receive a consistent nutrient intake throughout the day, leading to improved performance and health outcomes. However, this concept only works well for cattle already on a finishing diet and is not an appropriate method for adapting cattle to the finishing diet. When cattle are being adapted to a high concentrate diet feedlot operators often rely on residual feed in the bunk to allow cattle to consume concentrates with the option of including available forages into their diet if they experience a lower ruminal pH and instinctively select forages to help mitigate the ruminal pH. Therefore, adjusting feeding frequency to deliver TMR more frequently throughout the day can be an effective management strategy for cattle adapted to a high concentrate diet to minimize feed sorting and promote more uniform nutrient intake among cattle.

Particle size of the TMR provided also impacts the sorting potential of the diet. Improving the homogeneity of particle size, often by reducing long forage particles may improve DMI, especially when including a large proportion of low-quality forages (Campling and Freer 1966). Reducing the particle size can limit the bulkiness of the ration, reducing the ability to easily sort out the large particles, and within the rumen, increase the surface area for microbial attachment and increase the passage rate of the fiber (Stokes n.d.). Most of the research in this area has been completed with dairy cattle, as their TMR typically contains a large proportion of forages as compared to feedlot diets. Beauchemin et al. (1994a) compared two different forage to concentrate ratios and two different chop lengths of alfalfa silage fed to lactating Holstein cows. The authors found that when the cows had a higher forage content of their diet with a smaller particle size that the cows produced more milk, but on lower fiber diets the cows produced more milk when the particle size was longer. Thus, particle size is a management tool that each farm needs to manipulate based on the forage they are feeding. Hironakai et al. (1979) tested this concept with feedlot steers by manipulating the particle size of the diet with ground and pelleted feed and steam-rolled grain. They found that steers on the medium particle size ate more feed and had a higher ADG compared to the coarse and fine particle treatments. They attributed this response to the fine particle size causing more rumenitis and abnormal papillae, thereby causing the steers to reduce their feed intake in a response to buffer the rumen.

2.6. Conclusion

In western Canada, barley grain is the main energy source in finishing feedlot diets. Barley grain needs to be processed prior to feeding to break the hard outercoat of the kernel, but variability in kernel size within a load makes achieving optimal processing difficult. The balance between cracking all kernels while managing fine particle production is a problem feedlots encounter daily. Feedlots may invest in different processing techniques such as temper-rolling or steam-flaking to incorporate water into the kernel prior to processing to minimize fines and process more aggressively, but these techniques require expensive infrastructure and daily processing. Managing fine particles is important to minimize health concerns such as ruminal acidosis, bloat, laminitis, rumenitis, and liver abscesses. Feedlot diets in western Canada often contain a large proportion of grain with minimal forage resulting in dry diets that are easily sortable. A potential solution for feedlots is to manage feed sorting behaviour of cattle in conjunction with processing the barley to ensure adequate kernel processing. Liquid feed additives can be added to the diet to bind the TMR together and reduce the ability of the cattle to sort their diet, but the incorporation of LFA in the diet is dependent on regional availability and on-farm infrastructure to store and handle the product. A simple and readily available solution may be to include water in the TMR to reduce dietary sorting. Research studies have evaluated adding water into the TMR for dairy cattle, but there is no research to my knowledge investigating this concept for feedlot diets. With feedlot diets, preventing sorting may result in a more consistent diet being consumed throughout the day and among pen-mates thereby reducing the risk for ruminal acidosis induced by swings in nutrient consumption.

2.7. Hypothesis

The hypothesis was that as the amount of added water to the TMR increases, there will be a corresponding decrease in the sorting of the diet resulting in cattle consuming a diet that is more similar to the diet offered.

2.8. Objectives

The two studies in this thesis evaluated the effectiveness of adding water to the diet on feed sorting behaviour of beef cattle fed finishing diets. The objectives of this research were to evaluate whether adding water to the TMR affects DMI, water intake, sorting behaviour, ruminal fermentation, the site and extent of nutrient digestion, apparent total tract digestibility, growth performance, carcass composition, and meat quality in finishing beef steers.

3.0. IMPACT OF ADDING WATER TO A BARLEY-BASED FINISHING FEEDLOT DIET ON FEED SORTING BEHAVIOUR AND RUMINAL FERMENTATION FOR BEEF CATTLE

3.1. ABSTRACT

The objective of the study was to evaluate the effects of adding water to a barley-based feedlot diet as a strategy to bind ingredients together and reduce sorting. Eight ruminally cannulated Hereford crossbred growing beef steers (341.5 ± 25.1 kg starting BW) were used in a replicated 4×4 Latin square with four dietary treatments. Steers received the same diet on a DM basis with water added at 0% (CON), 10% (10W), 20% (20W), and 30% (30W) relative to the barley grain weight. The diets contained aggressively processed dry-rolled barley grain (PI = 62.2 ± 2.1%) to generate fines (3.2 ± 1.0%) to create a sortable diet. Data were analyzed using the MIXED procedure of SAS with linear and quadratic contrasts included to evaluate the effects of increasing water inclusion. Dry matter intake (DMI) and water intake increased linearly with water addition ($P < 0.01$ and $P = 0.04$, respectively). As water inclusion increased, the sorting index for the material on the pan linearly approached 100% ($P < 0.01$), indicating steers consumed more fine particles. The increase in fine particle consumption coupled with the increase in DMI caused the mean ruminal pH ($P < 0.01$) and maximum ruminal pH to decrease linearly ($P = 0.02$), while the duration pH <5.5 and lipopolysaccharide concentration increased linearly as water inclusion increased ($P = 0.02$ and $P < 0.01$, respectively). These data are interpreted to suggest that adding water to a barley-based feedlot diet reduces dietary sorting of fine particles and increases DMI at the expense of increasing the risk of ruminal acidosis when using aggressively processed barley grain.

3.2. INTRODUCTION

Feedlot diets in western Canada typically consist of a high proportion of barley grain with a minimal inclusion of roughage to optimize weight gain, feed conversion, and minimize days on feed (Koenig and Beauchemin 2011). Barley grain requires processing prior to feeding to expose the starchy endosperm (Beauchemin et al. 1994a), which is commonly achieved through dry-rolling or tempering-rolling. Variable barley kernel size is a common challenge faced by feedlots as it often leads to over-processing large kernels and under-processing small kernels. This is especially true for feedlots that rely on dry-rolling. Variable kernel size results from diverse factors including variety differences (Bradshaw et al. 1996), agronomic practices (Edney et al. 2012), growing conditions (Weston et al. 1993), and grain elevators blending multiple barley sources (Yang et al. 2013). Under-processing increases fecal starch losses (Koenig and Beauchemin 2011), making it economically undesirable for feedlots due to the high cost of barley grain. Conversely, over-processing of larger kernels may occur in an attempt to process the smaller kernels but raises the risk of digestive upset and ruminal acidosis due to the generation of more fine particles (Owens et al. 1998; Koenig et al. 2003).

Ruminants exhibit feed sorting as a natural behaviour to select for or against feeds or components of their diet. There are many factors that increase the ability for diets to be sorted including particle size (Leonardi and Armentano 2003), moisture content of the diet (Miller-Cushon and DeVries 2009), and forage inclusion (Miller-Cushon and DeVries 2017b). It has been reported that cattle fed high-grain diets sort the TMR for long particles as a strategy to alleviate a low ruminal pH (Yang and Beauchemin 2006; DeVries et al. 2014). However, this sorting poses challenges as it may lead to inconsistent growth among pen-mates and variability in ruminal acidosis risk.

A technique adopted by the dairy industry to deter cattle from sorting their diet involves adding water to the TMR to achieve approximately 50% DM (Lahr et al. 1983). This additional moisture binds ingredients during mixing, limiting the ability of cattle to sort the diet, and encouraging the intake of the formulated diet (Leonardi et al. 2005; Denißen et al. 2021). However, this approach has mixed results where some studies suggest that it may increase feed sorting behaviours and reduce DMI, potentially due to feed spoilage from the high moisture content (Miller-Cushon and DeVries 2009; Felton and DeVries 2010). In feedlot diets with high

dry grain inclusions, the high DM content offers an opportunity to add moisture as a binding agent while maintaining a DM concentration that mitigates the spoilage potential. I am not aware of any previous research that has explored the addition of water to feedlot diets as a management strategy to reduce feed sorting behaviours and promote consistent intakes.

The hypothesis of this study was that adding water to a finishing barley-based feedlot diet would cause the small particles from the dry-rolled barley to adhere to the larger particles in the silage, creating a homogenous mixture, thereby reducing feed sorting, maintaining DMI and water intake, and increasing ruminal fermentation and passage rate due to increased consumption of fine particles. Hence, the objective of this study was to investigate the effects of water addition to a finishing barley-based feedlot diet on DMI, water intake, feed sorting behaviour, ruminal fermentation, ruminal pool size, and digestibility.

3.3. MATERIALS AND METHODS

All steers and procedures used for this experiment were pre-approved by the University of Saskatchewan Animal Research Ethics Board (protocol 20220028, Saskatoon, SK, Canada) in accordance with the guidelines of the Canadian Council on Animal Care (Ottawa, ON, Canada).

3.3.1. Barley grain processing

Barley grain was sourced from a local feed company (Willow Mills Ltd., Osler, SK, Canada) from the 2022 growing season. The barley was processed by passing kernels through two 17.8-cm rollers with 6.3-grooves/cm and a groove depth of 2.4-mm (Apollo Machine & Products Ltd., Saskatoon, SK, Canada). The PI and proportion of fines produced were assessed. The PI was measured using a cox funnel with a 500-mL cup (Dimo's Labtronics, Winnipeg, MB, Canada). The volume weight of the processed grain was divided by the original unprocessed grain volume weight and expressed as a percentage (Yang et al. 2000). The proportion of fines was determined by sieving a 1-L sample through the 4- and 1.18-mm sieves, along with the pan of the PSPS (Spectrum Educational Supplies Ltd., Newmarket, ON, Canada) using the method described by Kononoff et al. (2003a). Barley grain collected in the pan was declared as fine particles and the proportional weight was calculated. The mean ± standard deviation (**SD**) values for the PI and percentage fines were 62.2 ± 2.1% and 3.2 ± 1.0%, respectively.

3.3.2. Steers and management

This experiment was conducted at the University of Saskatchewan Livestock Research Building (Saskatoon, SK, Canada). Eight Hereford steers, sourced from a single herd, were surgically fit with a 7.6-cm ruminal cannula (Model 4C, Bar Diamond Inc., Parma, ID, USA). The cannula was replaced with a 10-cm cannula (Model 9C, Bar Diamond Inc.) 21 d after the surgery. Prior to the beginning of the study, the steers were gradually transitioned (37 d with 7 intermediate diets) from a hay-based diet consisting of (% DM basis) 35.5% grass hay, 35.5% barley silage, 14.3% oat greenfeed pellet, 13.5% dry-rolled barley grain and 1.2% of a mineral and vitamin supplement to a high-grain finishing diet used as the base diet for the treatments (described below).

Steers were housed in individual pens (9 m^2) that were equipped with individual 24-hour access to fresh water, that were fit with flow meters (DLJ Water Meter, Hackensack, NJ, USA) connected to each water bowl. Pens had rubber mats on the floor and a suspended Jolly Ball (Horsemen's Pride, Streetsboro, OH, USA) for environmental enrichment. Steers were provided 2 h of outdoor access daily in an exercise yard at 0700 h. Pens were cleaned daily and feed refusals were removed and weighed prior to allocation of new feed at 0900 h.

3.3.3. Experimental design

The experiment was conducted as a replicated 4×4 Latin square design, with each square having a unique treatment sequence that was balanced for carry-over effects. Each period lasted 21 d including 16 d for adaptation and 5 d for data and sample collection. Diets were formulated using NASEM (2016) to meet or exceed nutrient requirements of a finishing beef steer with a starting BW of 341.5 ± 25.1 kg and growing at a rate of 2 kg/d. The diet consisted of (% DM basis) 88.0% dry-rolled barley grain, 7.7% barley silage, 4.1% mineral and vitamin premix that included monensin (33 mg/kg; Elanco Animal Health, Hillsdale, IN, USA), and 0.2% titanium dioxide (Table 3.1.). The same TMR was fed to all steers, with treatments differing in the inclusion of water included as a percentage of the barley grain: 0 (CON), 10 (10W), 20 (20W), and 30% (30W; Table 1). The addition of water resulted in dietary DM concentrations of 79.4% for CON, 74.2% for 10W, 69.7% for 20W, and 65.6% for 30W (Table 3.1.). All ingredients were manually weighed and hand mixed prior to feed delivery. The water addition range evaluated simulates dry-rolled barley (CON), temper-rolled barley (20W), and high-moisture barley (30W).

Silage and barley grain samples were collected every 4 and 7 d, respectively, and dried in a forced-air oven at 55°C until a constant weight was achieved to determine the DM content. The ingredient DM values were used to ensure that the diet mixed was equal to the formulated diet. Steers were abruptly changed to their respective treatment at the start of the study and the start of each period.

3.3.4. Measurements, samplings, and analysis

Steer BW was measured before feeding on d 0 and d 1 of each period and at the end of the study. The 2-d average weight was used to determine BW and report intake as a function of BW.

Water flow was recorded daily at 0700 h (during the 5-d collection period) to estimate water intake as described by Penner et al. (2020). Feed offered was recorded daily and provided *ad-libitum* once daily ensuring refusals were between 5 to 8% relative to the amount of feed provided on an as fed basis. The amount of feed refused was measured and recorded daily prior to feeding at 0700 h. During the 5-d collection phase within each period, all feed refusals were collected and composited by steer. In addition, during the 5-d collection phase, feed ingredients (800 g silage, 200 g barley, and 100 g mineral and vitamin premix) were collected daily, sampled in duplicate, and composited by ingredient to yield 2 samples for each ingredient. Both the feed refusals and the feed ingredients were stored at -20°C until further processing.

Refusal samples were thawed and subsampled to allocate into two 1-L containers for particle size separation using the PSPS in duplicate. Following particle size separation, one of the samples was dried in a forced-air oven at 55°C until achieving a constant weight to determine DM content. The sample was then ground to pass through a 1-mm screen using a Christie and Norris lab mill (Christy Turner Ltd., Ipswich, England, UK). Samples were sent to Cumberland Valley Analytical Services (CVAS; Waynesboro, Pennsylvania, USA) and analyzed for DM, ash, crude protein (**CP**), ADF, amylase neutral detergent fiber organic matter (**aNDFom**), starch, calcium (**Ca**), and phosphorus (**P**). Gross energy (**GE**) was determined in the lab at the University of Saskatchewan.

Table 3.1. Ingredient inclusion and chemical composition of finishing diets (means ± standard deviation) with no added water (CON), 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain as added water.

	Treatment			
	CON	10W	20W	30W
Ingredients, % DM				
Dry-rolled barley grain	88.0			
Barley silage	7.6			
Mineral and vitamin supplement[a]	4.2			
Titanium dioxide	0.2			
Ingredients, % as fed				
Dry-rolled barley grain	77.3±0.17	72.3±0.15	67.8±0.13	63.9±0.12
Barley silage	19.1±0.19	17.8±0.18	16.8±0.17	15.8±0.17
Water	-	6.5±0.03	12.3±0.05	17.3±0.07
Mineral and vitamin supplement[a]	3.4±0.02	3.2±0.02	3.0±0.02	2.8±0.02
Titanium dioxide	0.16	0.15	0.14	0.10
Chemical Composition, % DM[b]				
DM, %	79.4±0.36	74.2±0.31	69.7±0.28	65.6±0.25
Organic matter	94.6±0.11			
Crude protein	11.6±0.16			
Acid detergent fiber	7.8±0.25			
aNDFom[c]	17.8±0.81			
Starch	52.6±0.48			
Calcium	0.7±0.04			
Phosphorus	0.3±0.01			
Gross energy (cal/g)	4315±9.1			

[a]On a DM basis, the mineral and vitamin supplement contained 20.90% calcium (calcium carbonate), 0.14% phosphorus (no added source), 3.90% sodium (sodium chloride), 0.41% magnesium (potassium magnesium sulfate), 6.64% potassium (potassium magnesium sulfate), 11.12% chloride (sodium chloride), 1.61% sulfur (copper sulfate, zinc sulfate, manganese sulfate, and potassium magnesium sulfate), 380.8 mg/kg copper (copper sulfate), 1457.7 mg/kg zinc (zinc sulfate), 2121.4 mg/kg manganese (manganese sulfate), 757.4 mg/kg iron (no added source), 12.1 mg/kg iodine (ethylenediamine dihydroiodide), 2.8 mg/kg selenium, 99839 IU/kg vitamin A, 12615 IU/kg vitamin D3, 2642 IU/kg vitamin E, and 33 mg/kg monensin (Elanco Animal Health, Hillsdale, IN, USA).

[b]Chemical composition is expressed as the means with the standard deviation of the means.

[c]aNDFom = neutral detergent fiber corrected for organic matter.

For the silage, DM was determined using a two-step procedure. First, a partial DM was conducted using a method adapted from Goering and Van Soest (1970). This was followed by heating samples at 105°C for 3 h, as outlined in method 2.1.4 of the National Forage Testing Association (2006). For all other ingredients, DM was determined by drying the samples at 135°C, according to AOAC method 930.15 (AOAC 2000). Ash content was determined using a modified version of AOAC method 942.05 (2000). A 1.5 g sample was ashed for 4 h, followed by hot weighing. Organic matter (**OM**) was calculated by subtracting the ash content from 100%. Crude protein was determined using AOAC method 990.03 (2000), with a LECO FP-528 Nitrogen Combustion Analyzer (LECO, St. Joseph, MI, USA). Acid detergent fiber was measured following AOAC method 973.18 (2000), with a modification substituting Whatman 934-AH glass micro-fiber filters (1.5 µm particle retention; GE Healthcare Life Sciences, Chicago, IL, USA) for fritted glass crucibles. For aNDFom analysis, α-amylase and sodium sulfite were added, and the procedure was carried out using an ANKOM Fiber Analyzer (ANKOM Technology, Macedon, NY, USA). An ash correction was then performed by combusting the final glass fiber filter and sample at 535°C for 2 h. Gross energy (**GE**) was determine using a Parr 6400 Automatic Isoperibol Calorimeter (Parr Instrumental, Moline, Illinois, USA).

The feed ingredient samples were thawed at room temperature and divided into two samples. One sample was dried in a forced-air oven at 55°C to determine DM content and was then ground to pass through a 1-mm screen using a Christie and Norris hammer mill as previously described. Samples were sent to CVAS and analyzed for DM, CP, ADF, aNDFom, OM, Ca, P, and starch, and GE was determined at the University of Saskatchewan as previously described. The other ingredient samples were used to mix a 2 kg batch of treatment diets to determine particle size distribution using the PSPS in duplicate. For the sorting index, values greater than 100% indicate selective consumption, values less than 100% indicate selective avoidance, and values equal to 100% indicate no sorting (Leonardi and Armentano 2003). The assumption was made that all diets had the same particle size distribution, and therefore, all refusals were compared to the CON treatment. This assumption was made because the water simply changed the sorting potential of the diet; it did not remove the fine particles that were provided.

3.3.5. Ruminal fermentation and digesta pool sizes

Indwelling pH meters (Penner et al. 2006; Dascor, Escondido, CA, USA) were standardized using pH 4 and 7 buffer solutions (Fischer Chemical, Fair Lawn, NJ, USA) at 39°C prior to insertion on d 16 and removed on d 20 of each period enabling 96 h of continuous pH measurement. The weighted pH meter (2 kg) was placed in the ventral sac of the rumen and ruminal pH was recorded at 5-min intervals for 5 d. Upon removal, the pH systems were re-standardized, and the linear regressions obtained were used to convert the mV readings to pH (Penner et al. 2006). The pH data were summarized daily for minimum, maximum, and mean pH. In addition, the duration of time (min/d) and area (pH × min/d) that ruminal pH was <5.5 were calculated (Schwaiger et al. 2013).

Ruminal digesta was collected on d 17 with collection ending on d 21. Samples were collected every 12 h with a 3 h offset among days. Thus, the samples were collected at 0800 h and 2000 h on d 17, 1100 h and 2300 h on d 18, 1400 h on d 19, 0200 h and 01700 h on d 20, and 0500 h on d 21. Digesta (250 mL/region) was collected from the cranial, central, and caudal regions at the ruminal-fluid-ruminal-mat interface. Digesta was strained through two layers of cheese cloth and 10 mL was pipetted using a serological pipette into a sterile tube to evaluate LPS concentration and was immediately snap frozen in liquid nitrogen. This sample was then stored at -80°C until further analysis. Next, two 10-mL samples were collected and preserved in 2 mL of metaphosphoric acid (25% wt/v) for determination of the SCFA concentrations and in 2 mL of 1% sulfuric acid for ammonia-N analysis. The remaining solid and liquid ruminal digesta were returned to each steer.

Samples for SCFA and ammonia-N samples were mixed and were composited on an equal volume basis at the time of sampling to generate a single sample that represented every 3 h of a 24 h period for each steer and stored at -20°C until analysis. The SCFA concentrations were determined using gas chromatography (Khorasani et al. 1996) and ruminal ammonia nitrogen concentrations (NH_3-N) were determined using the phenol-hypochlorite method (Broderick and Kang, 1980).

Lipopolysaccharide concentration in ruminal fluid was analyzed as a composite sample. The original samples were thawed at 4°C for 24 h, and an equal volume from all samples within a period for each steer were composited into one sample. The composited samples were

immediately analyzed, and samples were processed and analyzed according to Gozho et al. (2005) using a β-G-Blocker kit (Lonza, Basel, Switzerland).

Rumen pool size was determined by completely evacuating the reticulo-rumen on d 21 of each period at 0700 h, prior to feeding. Digesta was collected, weighed, thoroughly mixed, and a 4-L sample was taken before returning digesta back to the steer (Pursley et al. 2020). The digesta subsample was separated into solid and liquid fractions using a wine press (Pleasant Hill Grain, Nebraska, USA). The weight of each fraction was recorded and immediately dried in a forced-air oven at 55°C until the weight remained consistent to determine DM content.

3.3.6. Site and extent of digestibility

A triple marker technique was used to assess the site and extent of digestion (France and Siddons 1986). Undigested neutral detergent fiber (**uNDF**) was used as a large particle (**LP**) phase marker, ytterbium chloride ($YbCl_3$; Siddons et al. 1985) as a small particle (**SP**) phase marker, and chromium ethylenediamine tetra-acetic acid (Cr-EDTA; Udén et al. 1980) as a fluid particle (**FP**) phase marker. The $YbCl_3$ and Cr-EDTA were directly infused into the rumen using a peristaltic pump beginning on d 14. Infusions were set to provide 1 L/d of solution to deliver 3.35 g of $YbCl_3$ (Brito et al. 2006) and 2.27 g of Cr-EDTA (Binnerts et al. 1968). A priming dose (500 mL with 1.675 g of $YbCl_3$ and 500 mL with 1.135 g of Cr-EDTA) was administered on d 14 to ensure that the concentration of markers in the rumen achieved steady-state before sample collections occurred (Benchaar et al. 1993). A subsample of each marker (12 mL) was collected and stored for analysis to confirm marker concentration. During infusions, steers continued to have daily exercise, by removing infusion lines to enable outdoor access. The infusate dispensed during outdoor access was collected for each steer and administered into the rumen when they returned to their pens and infusion lines were reconnected.

Omasal samples were collected following the technique described by Huhtanen et al. (1997) where the omasal canal was located by hand, a sampling tube was inserted, and a 500 mL sample was collected. This procedure followed modifications by Chibisa et al. (2012) where the sampling tube was inserted at each sampling timepoint as opposed to leaving the tube in for the duration of the collection period, to avoid disruptions to digestive function and to ensure proper placement. Omasal sampling was initiated (72-h after the initial marker infusion) on d 17 and ended on d 21. Omasal sample contents were collected every 12-h with a 3-h offset the next day,

following the same schedule as the ruminal digesta samples. Omasal digesta were composited to yield a single sample for each steer in each period and stored at -20°C until analysis.

The composite omasal samples were thawed at room temperature and separated into 3 digesta phases (LP, SP, and FP) as described by Reynal and Broderick (2005). Modifications to the procedure were made by drying the samples in a forced-air oven at 55°C until the sample weight remained constant on two consecutive days to calculate DM content. Once dry, the samples were ground to pass through a 1-mm screen (Retsch ZM 200, Haan, Germany).

To determine Cr-EDTA and $YbCl_3$ concentrations, a 1-g sample of each phase (LP, SP, FP) and 5 mL of the infusate were analyzed using inductively coupled plasma emission coupled with mass spectrometry (ICP-MS) with prior microwave digestion. The uNDF concentration in the ingredients (3 g), refusals (3 g), LP (1.5 g), and SP (2.1 g) phases were determined by incubating samples for 240 h in two ruminally cannulated dairy cows at the Rayner Dairy Research and Teaching Facility (Saskatoon, SK; Chibisa et al. 2012). Samples were weighed in triplicate into filter bags with 6-µm pores (ANKOM Technology, Macedon, NY, USA) and heat sealed (Impulse heat sealer, ANKOM Technology). Bags were placed into one of six weighted mesh bags (2 kg) that were randomly allocated to one of two cows, 3 bags per cow, and were inserted through the cannula and placed in the ventral sac of the rumen. After 240 h, bags were removed, rinsed thoroughly with cold water until the water ran clear, dried until achieving a constant weight at 55°C in a forced-air oven, and then analyzed for NDF using sodium sulfite and heat-stable α-amylase in a fibre analyzer (A200 fiber analyzer, ANKOM Technology). The uNDF concentration of each sample was the remaining NDF in the bag after the analysis was completed. The uNDF concentration of the diet was calculated by determining the uNDF concentration of each ingredient and multiplying it by the respective inclusion rate in the diet. The uNDF intake was calculated by subtracting the refused uNDF from the offered uNDF concentrations.

Once the concentrations of Cr, Yb, and uNDF were determined, the marker concentration in the fractions were evaluated. Marker failure for $YbCl_3$ was observed as the concentrations in the SP and FP phases were similar. As such, a dual marker method using $YbCl_3$ and uNDF was utilized to complete the calculations as described by Faichney (1975). The SP and the FP fractions were combined proportionally on a DM basis to create a new “liquid” fraction. The

liquid fraction and the LP phases were sent to CVAS for the analysis of DM and starch. Calculations were completed to mathematically recombine the fractions and calculate true digesta composition, digesta flow, and apparent ruminal and intestinal digestibility (France and Siddons 1986).

3.3.7. Apparent total tract digestibility

Titanium dioxide (TiO_2) was provided daily in the TMR and used to predict fecal output (Pereira et al. 2022). Fecal spot samples (200 g) were collected directly from the rectum at the same times as ruminal digesta and omasal digesta sampling. Samples were composited by steer on an equal as is basis and stored at -20°C until further analysis. Fecal samples were dried in a forced-air oven at 55°C and ground to pass through a 1-mm screen using a Christie and Norris hammer mill and were sent to CVAS for analysis of DM, CP, ADF, aNDFom, OM, Ca, P, and starch, and GE was determined at the University of Saskatchewan. Titanium dioxide concentration in the feed, refusal, and fecal samples were measured, and fecal output was calculated assuming 100% of the TiO_2 was excreted (Myers et al. 2004). A TiO_2 standard curve was determined for each run, and that curve was used for titanium concentration calculations. Apparent total-tract digestibility of DM, CP, ADF, aNDFom, OM, starch, and GE were calculated by dividing the difference between nutrient intake and excretion by nutrient intake and multiplying the divisor by 100%.

3.3.8. Statistical analysis

All statistical analysis were evaluated using the Statistical Analysis Systems software (SAS version 9.4, SAS Institute, Inc., Cary, NC, USA). Data were analyzed using the MIXED procedure with treatment as the fixed effect, and steer, period, and square as the random effects. One steer was removed prior to statistical analysis due to issues with cannula retention, and data collected were determined as outliers. Sorting behaviour was also analyzed using a two-tailed *t*-test to determine if individual treatment means differed from 100. Data and residuals were evaluated to confirm normal distribution using the UNIVARIATE procedure. All data were deemed to be normally distributed. Polynomial contrasts were used to evaluate the linear and quadratic responses to the addition of water in the TMR. All results were considered significant if the *P*-value was < 0.05 and a trend if $0.05 \leq P \leq 0.10$.

3.4. RESULTS

Increasing the inclusion of water did not affect the proportion of particles retained on the 19-mm sieve ($P < 0.41$; Table 3.2.), but linearly increased the proportions retained on the 8- and 4-mm sieves ($P < 0.01$). The proportion of particles retained on the 1.18-mm sieve decreased at an increasing rate (quadratic, $P = 0.04$), while for the pan, the proportion of particles present decreased at a decreasing rate (quadratic, $P = 0.01$) with the addition of water. All sorting index values were different from 100% ($P < 0.05$). There was no effect of adding water to the diet on the sorting index for the 19- and 8-mm sieves ($P \geq 0.27$) with cattle selecting for particles retained on the sieves (>100%). As water inclusion increased, the selective consumption of particles retained on the 4-mm sieve decreased ($P = 0.04$); while the selective avoidance of particles retained on the 1.18-mm sieve increased linearly ($P < 0.01$). Increasing water inclusion linearly decreased the selective avoidance of particles on the pan ($P < 0.01$).

Dry matter intake when expressed as kg/d and as %BW increased linearly as water addition increased ($P < 0.01$; Table 3.3.). Liquid water intake was not affected by the addition of water to the TMR ($P = 0.31$). Total water intake, calculated as a combination of liquid water intake and dietary added water, increased linearly as the inclusion of water increased, regardless of if expressed in L/d or as %BW ($P = 0.04$ and $P = 0.03$, respectively). Mean ruminal pH decreased at a decreasing rate (quadratic, $P = 0.05$) and maximum ruminal pH decreased linearly as water inclusion increased ($P=0.02$) but no effect was detected for minimum ruminal pH ($P \geq 0.14$). The duration that ruminal pH was <5.5 linearly increased as water inclusion increased ($P = 0.02$). However, there was no change in the area that ruminal pH was <5.5 ($P \geq 0.13$). There were no effects of water addition on the total SCFA concentration ($P \geq 0.46$) nor were there changes in the molar proportion of individual SCFA ($P \geq 0.10$), except for valerate which linearly decreased ($P = 0.04$) with increasing water inclusion. Ruminal ammonia-N concentration was not affected by the addition of water ($P \geq 0.53$). Increasing water inclusion linearly increased ruminal LPS concentration ($P < 0.01$).

Table 3.2. Dietary particle size distribution and sorting index values for steers fed a barley-based finishing diet with no added water (CON) or diets where water was added equating to 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain

						P-value	
	CON	10W	20W	30W	SEM	Linear	Quadratic
Diet particle size distribution, % as fed							
19-mm screen	1.78	1.43	1.88	1.35	0.218	0.41	0.69
8-mm screen	16.58	17.65	19.43	21.55	1.534	<0.01	0.49
4-mm screen	51.48	53.65	55.45	58.18	1.551	<0.01	0.81
1.18-mm screen	24.03	23.73	22.33	18.13	2.004	<0.01	0.04
Pan	6.23	3.60	1.90	0.85	0.318	<0.01	0.01
Sorting index[a], %							
19-mm screen	106.8*	105.7*	105.5*	106.1*	0.79	0.46	0.27
8-mm screen	106.7*	105.7*	105.4*	105.8*	0.76	0.37	0.33
4-mm screen	104.6*	103.6*	103.1*	102.4*	0.45	<0.01	0.60
1.18-mm screen	96.5*	94.9*	94.1*	94.1*	1.41	0.04	0.32
Pan	56.8*	71.2*	78.2*	85.2*	2.38	<0.01	0.11

[a]Sorting index was calculated as the actual intake of retained particles on each screen divided by the predicted intake (Leonardi and Armentano 2003)

*Indicates different from 100 ($P \leq 0.05$) using a two-tailed *t*-test.

Table 3.3. Dry matter intake (DMI), water intake, ruminal pH, short-chain fatty acid (SCFA) concentrations, ammonia-nitrogen (N) concentrations, and lipopolysaccharide (LPS) concentrations for steers fed a barley-based finishing diet with no added water (CON) or diets where water was added equating to 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain.

						P-value	
	CON	10W	20W	30W	SEM	Linear	Quadratic
DMI, kg	8.65	9.03	9.56	9.34	0.304	<0.01	0.10
DMI, % BW	2.00	2.07	2.20	2.16	0.107	<0.01	0.11
Liquid water intake, L	29.6	29.0	30.9	28.6	1.64	0.74	0.31
Total water intake, L[a]	31.9	32.2	35.1	33.7	1.73	0.04	0.30
Total water intake, % BW[a]	7.40	7.39	8.11	7.83	0.620	0.03	0.47
Ruminal pH							
Mean	5.91	5.72	5.73	5.71	0.083	<0.01	0.05
Maximum	7.03	6.77	6.81	6.72	0.099	0.02	0.27
Minimum	5.13	5.05	5.02	5.05	0.055	0.15	0.14
Duration pH < 5.5, min/day	442	625	637	651	106.8	0.02	0.14
Area pH < 5.5, pH × min	125.06	169.99	181.42	158.51	43.974	0.28	0.13
Total SCFA, m*M*	117.5	122.0	119.3	120.9	3.17	0.46	0.53
SCFA molar proportions, mmol/100 mol							
Acetate	44.79	43.91	44.73	45.05	2.038	0.63	0.42
Propionate	43.39	46.35	44.42	43.34	3.127	0.70	0.11
Butyrate	7.75	6.30	7.14	8.08	1.204	0.61	0.15
Isobutyrate	0.65	0.62	0.67	0.64	0.067	0.95	0.91
Valerate	1.83	1.55	1.60	1.41	0.186	0.04	0.73
Isovalerate	1.06	0.88	0.99	1.05	0.166	0.77	0.10
Caproate	0.46	0.45	0.45	0.44	0.093	0.81	1.00
Acetate:propionate	1.10	0.96	1.03	1.16	0.162	0.51	0.15
Ammonia-N, mg/dL	4.06	3.38	4.27	3.43	0.765	0.53	0.81
LPS, EU/μL	310.6	371.2	367.5	700.3	167.42	<0.01	0.15

[a]Total water intake was a calculated combination of both liquid water consumed and water added to the total mixed ration.

Total digesta weight, the weight of the solid fraction, and the DM concentration of all fractions reported on an as is basis, DM basis, or expressed as a percentage of BW were not affected by dietary water inclusion ($P \geq 0.10$; Table 3.4.). However, the weight of the free liquid fraction on an as is basis decreased linearly with increasing water addition ($P = 0.05$).

There was no change on the percentage of starch digested in the rumen as a percent of intake ($P \geq 0.38$), but there was a tendency for an increase in the amount of starch digested in the rumen as the amount of water increased in the TMR, when calculated as a daily rate ($P = 0.08$; Table 3.5.). There was no effect of adding water to the TMR for apparent total tract digestibility of DM, OM, CP, ADF, aNDFom, and starch ($P \geq 0.17$). There was no effect of adding water on digestible energy ($P \geq 0.24$). There was no effect of adding water on fecal output (DM basis) or fecal starch concentrations ($P \geq 0.27$).

Table 3.4. Digesta pool sizes for steers fed a barley-based finishing diet with no added water (CON) or diets where water was added equating to 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain.

						P-value	
	CON	10W	20W	30W	SEM	Linear	Quadratic
Ruminal digesta, kg as is							
Total	38.4	36.6	35.7	36.5	2.38	0.22	0.30
Solid fraction	8.9	8.7	9.3	9.5	0.69	0.33	0.70
Liquid fraction	29.6	27.9	26.5	27.1	1.84	0.05	0.25
Ruminal digesta, kg DM							
Total	4.23	4.13	4.28	4.53	0.376	0.29	0.44
Solid fraction	3.26	3.21	3.41	3.52	0.290	0.27	0.66
Liquid fraction	0.98	0.93	0.89	1.00	0.107	0.93	0.10
Ruminal digesta, %BW							
Total weight, kg as is	8.91	8.42	8.22	8.42	0.350	0.14	0.16
Total weight, kg DM	0.98	0.95	0.99	1.03	0.070	0.37	0.51

Table 3.5. Estimated fecal output and apparent total tract digestibility for steers fed a barley-based finishing diet with no added water (CON) or diets where water was added equating to 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain.

						P-value	
	CON	10W	20W	30W	SEM	Linear	Quadratic
Apparent ruminal digestibility							
Starch, %	95.6	96.3	96.9	95.7	1.06	0.81	0.38
Starch digested, kg/d	4.38	4.63	4.88	4.74	0.166	0.08	0.25
Apparent total tract digestibility, % dry matter (DM)							
DM	76.5	76.1	78.1	78.4	1.66	0.32	0.82
Organic matter	79.8	79.4	81.1	81.5	1.43	0.28	0.80
Crude protein	72.8	69.4	72.7	73.9	1.86	0.44	0.22
Acid detergent fiber	11.3	10.8	15.8	17.1	7.17	0.49	0.91
aNDFom[a]	42.1	40.8	47.3	46.1	4.42	0.36	0.99
Starch	97.0	97.1	97.0	97.8	0.33	0.17	0.33
Gross energy	76.9	77.0	79.0	79.4	1.59	0.19	0.93
Digestible energy, Mcal/kg DM	3.36	3.36	3.45	3.46	0.070	0.24	0.91
Fecal DM output, kg/d	1.99	2.16	2.08	2.02	0.149	0.98	0.42
Fecal starch, % DM	6.86	6.41	7.27	5.50	0.663	0.27	0.31

[a]aNDFom = neutral detergent fiber corrected for organic matter.

3.5. DISCUSSION

In the present study, the effect of water inclusion was evaluated as a strategy to limit dietary sorting by feedlot cattle. Previous research has reported that cattle with low ruminal pH sort against fine particles and sort for long particles (Yang and Beauchemin 2006; DeVries et al. 2008, 2014). Thus, dietary conditions were used that increase the risk for extensive ruminal fermentation and low ruminal pH; specifically, a low inclusion of forage (7.6% of the dietary DM) and aggressively dry-rolled barley grain (PI of 62.2 ± 2.1%) were used. The aggressively dry-rolled barley resulted in 3.2 ± 1.0% of the rolled barley weight as particles that passed through a 1.18-mm screen. The proportion of fines collected in the pan for the CON and 10W treatments were higher than theoretical contribution arising from the rolled barley, as the mineral was fed as a mash and contained particles that were retained on the pan. As hypothesized, the addition of water linearly increased the proportion of particles retained on the 8- and 4-mm sieves and linearly decreased the proportion of particles retained on the 1.18-mm sieve and the pan. The change in the particle size distribution of the TMR was interpreted to suggest that increasing water addition facilitated the binding of smaller particles to larger particles. The observed changes in TMR particle size distribution are consistent with other studies where the particle size distribution of the TMR changed with the DM concentration of the diet (Leonardi et al. 2005; Miller-Cushon and DeVries 2009; Felton and DeVries 2010).

In addition to the altered particle size distribution of the TMR, this study confirmed that water addition to the TMR linearly reduced the ability of cattle to sort against particles retained on the 4-mm sieve and the pan. However, cattle linearly increased sorting against particles retained on the 1.18-mm sieve and there were no differences among treatments for sorting against particles retained on the 8- and 19-mm sieve. This response is consistent with other study findings that have added moisture to the TMR as both water (Leonardi et al. 2005) or feed-grade molasses (DeVries and Gill 2012). In these studies, adding moisture to the diet reduced the sorting potential of the TMR. Leonardi et al. (2005) found that water addition decreased sorting (sorting index becoming closer to 100%) on the 8.98-, 5.61-mm sieves and the pan, which is similar to the findings of the present study. A major difference between the present study and that of Leonardi et al. (2005) is that they utilized a high forage TMR, which had a higher proportion

of longer particles, compared to the feedlot TMR fed in this study, which likely accounts for the sorting difference observed on the 8.98- and 8-mm sieves, respectively.

Increasing dietary water addition reduced mean ruminal pH in a quadratic manner and linearly increased the duration that pH was <5.5. The linear increase for the duration that ruminal pH was <5.5 further confirms the reduced ability of cattle to sort against fine particles as water inclusion increased. However, the increased DMI observed with increasing water addition confounds this outcome. Given the proportion of fine particles in the diet and the magnitude of change for DMI, it is likely that the increase in DMI had a greater effect. Despite the changes in DMI, altered sorting behaviour is particularly important as cattle experiencing low ruminal pH conditions have been reported to sort against fine particles and sort for long particles (Yang and Beauchemin 2006; DeVries et al. 2008, 2014). While all steers in the present study sorted for long particles and against particles retained on the pan, increasing water addition reduced sorting behaviour and prevented sorting from alleviating low ruminal pH.

In addition to the linear increase for the duration that ruminal pH was <5.5, a linear increase in ruminal LPS concentration with increasing water inclusion was observed. Past research has reported that LPS concentration increases with increasing dietary grain concentration (Gozho et al. 2007). While diets in the present study did not differ in starch concentration, increasing water inclusion linearly increased DMI, reduced the ability to sort against small particles, and tended to increase the quantity of starch digested in the rumen. All of the previously mentioned factors led to more starch being digested in the rumen daily thereby helping to explain the increase in ruminal LPS. Moreover, low ruminal pH may increase the lysis of gram-negative bacteria (Monteiro and Faciola 2020) resulting in greater ruminal LPS concentrations. Additionally, there was a linear decrease in the molar proportion of valerate with increasing dietary water addition, likely attributed to the decrease in ruminal pH. This may be indicative of altered microbial end products; however, the differences in valerate proportions were relatively small, and it is unclear what impact, if any, this may have had within the rumen. Overall, while the greater duration that ruminal pH was <5.5 and greater increase in ruminal LPS concentration are not desirable outcomes and indicate a greater risk of ruminal acidosis, they confirm that water addition prevented sorting of dietary components and selection against small particles.

There were no detectable differences in SCFA concentrations (except for valerate already discussed), rumen ammonia concentration, ruminal pool size, and total tract digestibility. These findings suggest that the changes in the sorting index were not strong enough to elicit major changes in ruminal fermentation profiles beyond ruminal pH. Similarly, there was a linear decrease in the liquid fraction of the rumen on an "as is" basis but when converted back to DM, the fractions were nearly equal, indicating that the detected significance may not be meaningful. Additionally, there was no change in the percentage of starch digested in the rumen; however, a very high proportion of starch was digested in the rumen, approximately 96%. This is likely due to the aggressively processed barley that was fed, and the large proportion of rapidly fermentable small particles.

Interestingly, liquid water intake did not change among treatments, and adding water to the TMR increased total water intake. This is a somewhat unexpected response as research by Denißen et al. (2021) found that cattle decreased their water intake as the moisture in the diet increased, maintaining a consistent total water intake. In the present study, cattle did not change their drinking behaviour, and therefore increased the total water intake as water was added to the TMR. Additionally, although the steers experienced conditions reflective of ruminal acidosis (Penner et al. 2007) based on the low ruminal pH and high LPS concentrations, they did not reduce DMI. Instead, DMI increased linearly as the amount of water added to the TMR increased. This response was unexpected, and further research is needed to confirm if an increase in DMI is a repeatable response.

3.6. CONCLUSION

This research demonstrates that adding water to finishing feedlot diets binds fine particles to other components in the TMR, thereby altering sorting behaviour of the cattle. Adding water to the TMR increased DMI and reduced the sorting potential of the diet, resulting in the steers consuming a higher proportion of fine particles and more starch, confirmed by a decrease in mean ruminal pH, an increase in the duration pH > 5.5, and an increase in ruminal LPS concentration. However, the changes in sorting index were not different enough to change SCFA concentrations, ruminal pool size, and total tract digestibility. As such, adding water to feedlot

diets appears to encourage a more consistent nutrient intake throughout the day without having adverse effects on ruminal fermentation or digestibility, but does increase the risk for ruminal acidosis when barley grain is processed aggressively.

4.0. IMPACT OF ADDING WATER TO A BARLEY-BASED FINISHING DIET FOR STEERS ON GROWTH PERFORMANCE, FEED SORTING BEHAVIOUR, AND CARCASS CHARACTERISTICS

4.1. ABSTRACT

The objective of this study was to evaluate the effect of water addition to barley-based diet on feed sorting behaviour, DMI, growth performance, and carcass characteristics for finishing steers. One hundred twenty steers (331.0 ± 31.0 kg starting BW) were stratified into 20 pens (6 steers/pen, 5 pens/treatment) and fed a finishing diet that included water at 0% (**CON**), 10% (**10W**), 20% (**20W**), or 30% (**30W**) relative to the weight of the barley grain. Steers were fed for 150 to 181 d, and upon completion of the feeding period, were slaughtered and carcass merit and characteristics data were collected. Sorting index values for particles retained on the 19-, 4-, and 1.18-screens, and the pan were quadratically affected ($P \leq 0.02$) such that the magnitude of the sorting decreased (values moved towards 100%) at a decreasing rate as water inclusion increased. No differences ($P \geq 0.11$) were detected for DMI, ADG, G:F ratio, carcass characteristics, rumen epithelial damage, and liver abscess scores. Increasing water linearly reduced variability within a pen for marbling scores ($P = 0.05$). This study suggests that adding water at 21.9% of the barley grain weight to the finishing diet may be optimal to reduce dietary sorting by pen-fed finishing steers, resulting in more consistent fat deposition among steers.

4.2. INTRODUCTION

Western Canadian finishing feedlot diets typically include a high proportion of barley grain with minimal inclusion of silage (Koenig and Beauchemin 2011a; Chibisa et al. 2020), resulting in a dry, sortable diet. Feedlot cattle may exhibit feed sorting behaviours, selecting for or against individual feeds or components within a TMR (Llonch et al. 2020; Pursley et al. 2020). Cattle may sort components of their diet based on factors such as palatability, forage content, or particle size (Nombekela et al. 1994; Leonardi and Armentano 2003; Llonch et al. 2020). Feedlot cattle with low ruminal pH have been reported to selectively consume long particles (Yang and Beauchemin 2006; DeVries et al. 2014) suggesting that sorting behaviour at an individual level may occur within a pen. Sorting behaviour of individual cattle may alter the composition of the remaining feed in the bunk, and hence the diet consumed by other cattle within the same pen. Theoretically, sorting behaviour of individual cattle may lead to inconsistent nutrient intake and growth among cattle within a pen and may alter the risk for digestive disorders such as bloat and ruminal acidosis. However, sorting activity in group-fed cattle is rarely analyzed, possibly due to the perception that feed sorting is minimized through management strategies such as multiple feedings and adjustments to the amount of feed provided, aiming to minimize residual feed in the bunk the following day (Pritchard and Bruns 2003).

The addition of water to diets has been adopted by the dairy industry to help bind ingredients during mixing, thereby limiting sorting ability (Lahr et al. 1983). However, the addition of water has mixed results. Adding water to a TMR may reduce dietary sorting, promote intake of NDF, and improve milk fat concentration for dairy cattle (Leonardi et al. 2005; Fish and DeVries 2012; Denißen et al. 2021). However, it has also been shown that adding water may increase sorting behaviours and reduce DMI, potentially due to feed spoilage from a higher moisture content when combined with high ambient temperatures (Miller-Cushon and DeVries 2009; Felton and DeVries 2010). Given the high DM concentration for feedlot diets (Galyean and Defoor 2003; Samuelson et al. 2016; Chibisa et al. 2020), adding water may function as a binder, limiting sorting potential. To my knowledge, there are no previous studies exploring water addition to feedlot diets as a management strategy to reduce sorting behaviour and the impact on growth performance of feedlot cattle.

I hypothesized that adding water to a finishing barley-based feedlot diet would reduce feed sorting, increase DMI, increase growth performance, and reduce variation in carcass characteristics of beef steers. Thus, the objective of this study was to investigate the effects of water addition to a finishing barley-based feedlot diet on feed sorting behaviour, DMI, growth performance, and carcass characteristics of finishing steers.

4.3. MATERIALS AND METHODS

All steers and procedures used in this experiment were pre-approved by the University of Saskatchewan Animal Research Ethics Board (protocol 20220028, Saskatoon, SK, Canada) and the Agriculture and Agri-Food Canada Research Board, Lacombe Research and Development Center (protocol 202303, Lacombe, AB, Canada) in accordance with the guidelines of the Canadian Council on Animal Care (Ottawa, ON, Canada).

4.3.1. Steers and management

This experiment was conducted at the Agriculture and Agri-Food Canada (AAFC) Lacombe Research and Development Centre (Lacombe RDC) in Alberta (Canada). One hundred twenty Angus-based crossbred beef steers (331.0 ± 31.0 kg BW) from the AAFC Lacombe RDC cow-calf herd were used. After weaning, steers were preconditioned to eat from fence-line concrete bunks. Steers were housed in outdoor dry-lot pens measuring 12 × 18.5 m, with 2.5-m high windbreaks along the north and south sides, and an automatic water bowl in each pen. Canola straw bedding was provided as needed throughout the study.

One day prior to the start of the experiment and before feeding, steers were weighed and implanted with Component E-S (200 mg progesterone, 20 mg estradiol benzoate, and 29 mg tylosin tartrate, Elanco Animal Health, Hillsdale, IN, USA). Steers were also treated for internal and external parasites (Ivomec, Boehringer Ingelheim Canada, Burlington ON, Canada). Steers were then stratified by BW and randomly assigned to 1 of 5 groups. Groups were randomly assigned to 1 of 20 pens (5 pens/treatment, 6 steers/pen), and pens were randomly assigned to 1 of 4 dietary treatments. Steers were weighed again the following day, prior to feeding, to calculate the average BW at the start of the study. Steers received a terminal implant (Component

TE-S; 120 mg trenbolone acetate, 24 mg estradiol, and 29 mg tylosin tartrate, Elanco Animal Health) on d 84 of the study.

Steers were monitored daily for health status by trained staff and treated as necessary. No steers were removed from the experiment. However, two individual steers were treated for respiratory illness.

4.3.2. Treatments and data and sample collection

At the start of the study, steers were gradually transitioned from their post-weaning diet containing (DM basis) 9.6% grass hay, 85.3% silage, and 5.2% of a 20% protein supplement (Masterfeeds, Red Deer, AB, Canada) to their respective finishing diet over 21 d using 6 steps (Table 4.1.). Treatments were applied during the transition period. Treatment diets were formulated using NASEM (2016) to meet or exceed nutrient requirements of a finishing beef steer with a starting BW of 330 kg, a final BW of 650 kg, and growth rate of 1.8 kg/d. The finishing diet consisted of (DM basis) dry-rolled barley grain (88.0%), barley silage (9.6%), and a mineral and vitamin premix (2.4%) that included monensin (Elanco Animal Health) to achieve a dietary concentration of 33 mg/kg (Table 4.2.). Dry-rolled barley grain was purchased from a local supplier (Masterfeeds, Red Deer, AB, Canada), and the PI and the proportion of fines produced were assessed following the same procedures as described in Chapter 3. The mean ± SD values for the PI and percentage fines were 84.2 ± 3.4% and 2.1 ± 1.0%, respectively.

The same TMR (DM basis) was fed to all steers, with treatments differing only in the inclusion of water. The amount of water added was calculated as a percentage of the barley grain weight, resulting in 0% (**CON**), 10% (**10W**), 20% (**20W**), and 30% (**30W**; Table 4.2.) water addition. The resulting dietary DM concentrations were 78.7% for CON, 73.6% for 10W, 69.1% for 20W, and 65.1% for 30W. Steers were fed once daily between 0800 and 1100 h, with the amount of feed delivered to achieve *ad-libitum* intake while minimizing residual feed in the bunk. Ingredients were weighed individually into a feed delivery truck (Supreme Vertical Feed Mixer; Supreme International, Wetaskiwin, AB, Canada) with two vertical screws, and all diets were mixed for 5 minutes prior to delivery.

Throughout the study, silage samples were collected weekly and dried until achieving a constant weight in a forced-air oven at 80°C to determine the DM concentration. The DM

Table 4.1. Ingredient inclusion of diets used to transition steers to a barley-based finishing diet with 0% (CON), 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain as added water.

	Day 1 to 5	Day 6 to 9	Day 10 to 13	Day 14 to 17	Day 17 to 20	Day 21
Ingredients, % DM						
Dry-rolled barley grain	47.6	61.0	69.0	76.0	81.0	88.0
Barley silage	50.0	36.6	28.6	21.6	16.6	9.6
Mineral and vitamin supplement[a]	2.4	2.4	2.4	2.4	2.4	2.4
Ingredients, % as fed						
CON Dry-rolled barley grain	31.3	44.1	53.2	62.1	69.1	80.1
Barley silage	67.3	54.3	45.2	36.2	29.1	18.0
Water	-	-	-	-	-	-
Mineral and vitamin supplement[a]	1.4	1.5	1.6	1.7	1.8	1.9
10W Dry-rolled barley grain	30.5	42.5	50.8	58.9	65.2	74.9
Barley silage	65.6	52.3	43.2	34.4	27.4	16.8
Water	2.7	3.7	4.4	5.1	5.7	6.5
Mineral and vitamin supplement[a]	1.4	1.5	1.6	1.6	1.7	1.8
20W Dry-rolled barley grain	29.7	41.0	48.7	56.0	61.7	70.3
Barley silage	63.9	50.5	41.4	32.7	26.0	15.8
Water	5.2	7.1	8.5	9.8	10.7	12.2
Mineral and vitamin supplement[a]	1.3	1.4	1.5	1.6	1.6	1.7
30W Dry-rolled barley grain	28.9	39.6	46.7	53.4	58.6	66.3
Barley silage	62.3	48.7	39.7	31.2	24.6	14.9
Water	7.6	10.3	12.2	13.9	15.3	17.3
Mineral and vitamin supplement[a]	1.3	1.4	1.4	1.5	1.5	1.6

[a]On a DM basis, the mineral and vitamin supplement contained 24.01% calcium, 0.07% phosphorus, 4.27% sodium, 0.35% magnesium, 7.60% potassium, 12.87% chloride, 0.15% sulfur, 439.6 mg/kg copper, 1676.4 mg/kg zinc, 24442.6 mg/kg manganese, 868.6 mg/kg iron, 14.0 mg/kg iodine, 3.3 mg/kg selenium, 111559 IU/kg vitamin A, 13900 IU/kg vitamin D3, 3028 IU/kg vitamin E, and 33 mg/kg monensin (Elanco Animal Health, Hillsdale, IN, USA).
[b]Chemical composition is expressed as the means with the standard deviation of the means.

Table 4.2. Ingredient inclusion and chemical composition of finishing diets (means ± standard deviation) with 0% (CON), 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain as added water.

	Treatment			
	CON	10W	20W	30W
Ingredients, % dry matter (DM)				
Dry-rolled barley grain		88.0		
Barley silage		9.6		
Mineral and vitamin supplement[a]		2.4		
Ingredients, % as fed				
Dry-rolled barley grain	79.7±0.93	74.6±0.83	70.0±0.76	66.0±0.70
Barley silage	18.4±0.95	17.2±0.89	16.1±0.85	15.2±0.81
Water	-	6.5±0.13	12.2±0.24	17.2±0.31
Mineral and vitamin supplement[a]	1.9±0.04	1.8±0.04	1.7±0.03	1.6±0.03
Chemical Composition, % DM[b]				
DM, %	78.7±1.74	73.6±1.52	69.1±1.34	65.1±1.19
Organic matter		95.5±0.63		
Starch		53.9±1.03		
aNDFom[c]		17.5±0.50		
Crude protein		12.6±0.29		
Acid detergent fiber		9.0±0.41		
Calcium		0.6±0.01		
Phosphorus		0.3±0.03		

[a]On a DM basis, the mineral and vitamin supplement contained 22.88% calcium (calcium carbonate), 0.07% phosphorus (no added source), 4.20% sodium (sodium chloride), 12.39% chloride (sodium chloride and potassium chloride), 0.62% magnesium (magnesium oxide), 6.97% potassium (potassium chloride), 0.17% sulfur (copper sulfate and ferrous sulfate), 0.02 cobalt (no added source), 438.0 mg/kg copper (copper sulfate), 1666.1 mg/kg zinc (zinc oxide), 2590.9 mg/kg manganese (manganese oxide), 2006.9 mg/kg iron (ferrous sulfate), 16.0 mg/kg iodine (ethylenediamine dihydroiodide), 3.2 mg/kg selenium, 110 KIU/kg vitamin A, 15 KIU/kg vitamin D3, 2970 IU/kg vitamin E, and 1367.2 mg/kg monensin (Elanco Animal Health, Hillsdale, IN, USA).

[b]Chemical composition is expressed as the means (n=3) with the standard deviation of the means.

[c]aNDFom = neutral detergent fiber corrected for organic matter.

coefficients were used to ensure that the diet provided was the same as the formulated diet. Additional samples of barley silage, dry-rolled barley grain, and the mineral and vitamin premix were collected every three weeks. Samples were sieved in duplicate with the PSPS (Spectrum Educational Supplies Ltd., Newmarket, ON, Canada) in accordance with the ASAE Standard S424.1 method (ANSI, 1998). The 19-, 8-, 4-, 1.18-mm sieves, and the pan were used for all ingredients, and once separated, samples were recombined and dried in a forced-air oven at 55°C until the weight remained constant. The barley silage and dry-rolled barley grain were then ground to pass through a 1-mm screen using a Christie and Norris lab mill (Christy Turner Ltd., Ipswich, England, UK). Samples of silage from the first 15 weeks were composited into two samples. Due to a change in the silage pit used, a third sample was prepared using samples collected over the last 12 weeks. The dry-rolled barley grain and the mineral and vitamin premix were each composited into two 6-week samples, and a third sample was composited from the last 8 weeks of the study, resulting in 3 individual samples for each ingredient being analyzed. Composited samples were sent to CVAS (Waynesboro, Pennsylvania, USA) and analyzed for DM, OM, CP, ADF, aNDFom, starch, Ca, and P as described in Chapter 3.

Every 21-d during the study, steers were individually weighed at 0800 h. On weigh days, feeding was delayed until all the steers had been weighed and returned to their pen. The live BW data recorded throughout the study was used to calculate ADG by regressing BW with the day of study without adjustments for gastrointestinal tract fill. On the same day, feed bunks were cleaned, and residual feed was removed and weighed. Feed refusals as a percentage of feed offered for the duration of each 3-wk feeding period were 2.8 ± 1.9% for CON, 2.0 ± 2.1% for 10W, 1.3 ± 1.2% for 20W and 1.4 ± 1.2% for 30W. A 2-kg sample of feed refusal was collected to determine the particle size distribution using the PSPS as described previously. The samples were collected at four time-points (d 105, 126, 147, and the final day that the steers were in their pen (d 153, 160, 167, 174, or 181)). The quantity and particle distribution of the refusals was compared to the diet particle size distribution of the CON to determine sorting index (Leonardi and Armentano 2003). Samples of refusals were also used for the measurement of DM as described above for feed samples. The daily DMI was calculated by subtracting the DM refused from the DM offered and dividing by number of steers and days. Values obtained from each 3-wk duration were averaged over the duration of the study. The G:F was calculated by dividing

the pen-level ADG by the average DMI. The dietary net energy values for maintenance (**NE_m**) and gain (**NE_g**) were calculated based on animal performance as described by NASEM (2016).

On d 83 and 148, a 250-mL sample of fresh feces was collected directly from six fresh fecal pats in each pen to yield a final sample of 1.5 L. Samples were dried in a forced-air oven at 55°C until the weight remained constant and were then ground to pass through a 1-mm screen using a Christie and Norris hammer mill. Ground samples were analyzed for starch at CVAS using wet chemistry, following the procedure of Hall (2009).

4.3.3. Carcass merit

Slaughter dates were pre-planned based on facility availability, and feed and water were not restricted before slaughter. For slaughter, steers were blocked by BW based on the most recent BW measurement, and the heaviest pen for each treatment was selected. Prior to slaughter, steers were weighed on a single day. On the first slaughter day in each week, the heaviest 3 steers from each treatment pen were selected and harvested on Friday, with the remaining 3 steers harvested the following Monday. The staggered schedule resulted in 150 to 181 d on feed, for an average ending BW of 604.5 ± 39.7 kg. Block 1 had an average ending BW of 632.5 ± 24.1 kg and days on feed (**DOF**) of 151.5 d, block 2 was 610.0 ± 30.7 kg and DOF of 158.5, block 3 was 610.0 ± 26.0 kg and DOF of 165.5, block 4 was 605.8 ± 28.3 kg and DOF of 172.5, and block 5 was 564.4 ± 51.0 kg and DOF of 179.5.

Steers were weighed, euthanized by captive bolt stunning followed by exsanguination, and then dressed by removing the head, feet, and hide. The organs were removed, and the carcass was split along the spine, with each half weighed. The hanging tender, kidney, pelvic, and heart (**KPH**) fat were removed and individually weighed. Each carcass half was then weighed again to determine the hot carcass weight (**HCW**). Dressing percentage (**DP**) was calculated as the ratio of HCW (without KPH) to the shrunk adjusted live weight, using 4% shrink. Carcasses passed through a pasteurizing shower, were hung in a cooler, and chilled at 2°C for either 72 h (for steers slaughtered on Friday) or 48 h (for steers slaughtered on Monday).

After the organs had been inspected by a Canadian Food Inspection Agency (Ottawa, ON, Canada) inspector, all livers were visually analyzed and palpated to determine the presence of abscesses and scars. The livers were categorized into no abscesses (clear), up to four small

abscesses (under 2.54 cm in diameter, minor), or more than four small abscesses or one or more large abscess (greater than 2.54 cm in diameter, severe) as adapted from Brown and Lawrence (2010).

The reticulo-rumen was isolated and opened by cutting along the omasal groove (omasal orifice to the esophagus) caudally to the right of the esophagus, along the dorsal side of the rumen to the right of the spleen and continued as far caudally as accessible (caudal-dorsal blind sac). The reticulo-rumen contents were emptied, and the empty rumen and reticulum were rinsed with cold water. The caudal-dorsal blind sac, caudal-ventral blind sac, ventral sac, cranial sac, and reticulum regions were assessed for damage by trained technicians blinded to treatments. Observations for papillae redness and papillae clumping were recorded, and areas of ruminal epithelial damage (cm^2) were measured with a ruler to determine total surface area of rumen epithelial damage. Areas of damage were assumed to be rectangular in shape, and the maximum length and width were recorded and used for the calculations.

After the conventional chilling, carcasses were weighed to determine the cold carcass weight (**CCW**). The left and right sides were then weighed and shrink loss was calculated as the difference between the HCW and CCW. The carcasses were knife-ribbed between the 12^{th} and 13^{th} ribs. After 20 minutes of oxygen exposure, full Canadian-grading data was assessed at the 12^{th} to 13^{th} rib by a Canadian Beef Grading Agency (**CBGA**) certified grader. The grading assessments included fat thickness (at the three-quarter position from the spinous process using the yield ruler), ribeye area (**REA**; measured using a grid), and marbling score using the United States Department of Agriculture beef marbling pictorial standards (United States Department of Agriculture 2017, 2024). The retail cut yield (**RCY**) was calculated using the CBGA yield ruler (Canadian Beef Grading Agency 2024). The results for the fat thickness, REA, marbling score, and RCY were averaged between the two sides of the carcass. When the two sides had a different categorical quality grade and yield grade score, the better score of the two sides was selected. At either 2 or 3-d postmortem (depending on slaughter day), the left side of the carcasses were fabricated into primal cuts including the chuck, rib, loin, round, brisket, foreshank, plate, and flank. Each primal cut was scanned with a GE Lunar dual-energy x-ray absorptiometry (**DEXA**) unit (GE Lunar, General Electric, Madison, WI, USA) using the left leg option on standard mode using the model by López-Campos et al. (2018). The DEXA equations are an alternative to the

traditional cut-out approach to estimate tissue composition of fat, lean, and bone percentages comprising each primal cut.

4.3.4. Calculations and statistical analysis

Means and the SD for response variables within each pen were calculated to assess variability among steers within the pen. Statistical analysis for continuous variables were performed using Statistical Analysis Systems software (SAS version 9.4, SAS Institute, Inc., Cary, NC, USA). Data were analyzed using the MIXED procedure as a randomized complete block design, with the pen as the experimental unit, treatment as the fixed effect, and block as the random effect. The block was the week of slaughter. Polynomial contrasts were then used to examine the linear and quadratic responses to the addition of water in the TMR. Fecal starch and sorting data were analyzed using the same model with week of measurement included as a repeated measure, using the most appropriate covariance structure determined based on the lowest Akaike and Bayesian Information Criterion values. When a treatment × week interaction was detected, the slice function was used to compare treatments within a week. Sorting behaviour was further evaluated using a two-tailed *t*-test to determine if individual treatment means differed from 100. Data and residuals were evaluated to confirm if they were normally distributed using the UNIVARIATE procedure of SAS (Cary, NC, USA). All data were deemed to fit the criteria for normal distribution.

Categorical data (yield grade, quality grade, and liver scores) were initially assessed using the FREQ procedure of SAS (Cary, NC, USA), where the counts for each score were calculated and summarized into a contingency table. Subsequently, the GLIMMIX procedure of SAS (Cary, NC, USA) was used with conditional logistic regression, maximum likelihood estimation, and the Laplace approximation to generate odds ratios for each treatment relative to the CON. The model included treatment as the fixed effect and block as the random effect, using multinomial distribution with a cumulative logit link function. Polynomial contrasts were applied to evaluate the linear and quadratic responses. For all analyses, results were considered significant if the *P*-value was ≤ 0.05 and a tendency if $0.05 < P \leq 0.10$.

4.4. RESULTS

4.4.1. Body weight, dry matter intake, and growth performance

By study design, the initial BW of the steers did not differ among treatments ($P \geq 0.97$; Table 4.3.). Final BW, DMI expressed as kg/d and %BW, ADG, G:F, NE_m, and NE_g were not affected by the addition of water ($P \geq 0.41$). There was no effect of treatment on the SD for initial BW, final BW, or ADG ($P \geq 0.33$). Additionally, fecal starch concentrations were not affected by the addition of water ($P \geq 0.39$).

4.4.2. Sorting behaviour

Sorting index values for the 19-, 8-, and 4-mm sieves were not affected by the treatment × week interaction ($P \geq 0.22$; Table 4.4.); whereas the particles on the 1.18-mm sieves and the pan were affected by the treatment × week interaction ($P = 0.03$ and $P = 0.04$, respectively). For CON cattle, the sorting index value generally decreased with advancing days on feed, while no differences were observed among treatments over time when water was added (Figure 4.1. and 4.2.). Sorting index values for the 19-mm sieve decreased at a decreasing rate with increasing water inclusion (quadratic, $P < 0.01$) and week of study (data not shown, $P < 0.01$). There was a linear reduction in the sorting index for particles retained on the 8-mm sieve ($P < 0.01$) with CON steers sorting for those particles and steers fed 20W and 30W sorting against those particles. Sorting index values for the 4-mm sieve also decreased at a decreasing rate with increasing water inclusion (quadratic, $P < 0.01$) and week of study (data not shown, $P < 0.01$). Conversely, the sorting index for the particles retained on the 1.18-mm sieve increased at a decreasing rate with the addition of water (quadratic, $P = 0.01$) and week of study (data not shown, $P < 0.01$). The particles retained in the pan also increased at a decreasing rate with the addition of water (quadratic, $P < 0.01$), week of study (data not shown, $P < 0.01$), but the sorting index values for 20W and 30W treatments were not different than 100%.

4.4.3. Carcass characteristics, rumen epithelial damage, and liver scores

The addition of water to the TMR did not affect carcass weight, DP, or shrink loss ($P \geq 0.23$; Table 4.5.). Similarly, the standard deviation within a pen for HCW, CCW, DP, shrink loss, and RCY were not affected by the addition of water ($P \geq 0.16$). Weights for the hanging tender, pelvic fat, and heart fat were not affected ($P \geq 0.20$), though there was a tendency for kidney fat

Table 4.3. Growth performance of steers fed a barley-based finishing diet with 0% (CON), 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain as added water

						P-value	
Variable	CON	10W	20W	30W	SEM	Linear	Quadratic
Initial body weight (BW), kg	331	331	331	330	14.9	0.97	0.99
Initial BW standard deviation (SD), kg	8.8	10.4	9.5	9.0	1.62	0.97	0.47
Final BW, kg	602	606	600	611	13.1	0.56	0.71
Final BW SD, kg	32.7	27.9	23.7	31.5	6.62	0.79	0.33
Dry matter intake (DMI), kg/d	9.4	9.7	9.4	9.7	0.31	0.52	0.90
DMI, % BW	2.08	2.14	2.09	2.12	0.044	0.63	0.68
Average daily gain, kg/d	1.71	1.75	1.72	1.78	0.057	0.46	0.79
Average daily gain SD, kg/d	0.174	0.168	0.131	0.169	0.0422	0.77	0.59
Gain:feed, kg BW/kg DMI	0.182	0.181	0.182	0.186	0.0044	0.52	0.62
NE_m, Mcal/kg[a]	1.93	1.90	1.91	1.92	0.032	0.74	0.41
NE_g, Mcal/kg[a]	1.28	1.25	1.27	1.27	0.028	0.74	0.41
Fecal starch concentration, % of dry matter	16.52	16.81	17.24	15.91	0.933	0.74	0.39

[a]Net energy (NE) values for maintenance and gain were calculated based on animal performance as described by Zinn et al. (2002) and Zinn and Shen (1998).

Table 4.4. Sorting behaviour of steers fed a barley-based finishing diet with 0% (CON), 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain as added water

						P-value			
Variable	CON	10W	20W	30W	SEM	Week[b]	Treatment × Week	Linear	Quadratic
Diet particle size distribution, % as fed									
19-mm screen	2.76	-	-	-					
8-mm screen	11.25	-	-	-					
4-mm screen	76.33	-	-	-					
1.18-mm screen	6.45	-	-	-					
Pan	3.41	-	-	-					
Sorting index[a], %									
19-mm screen	103.2*	101.7*	101.2*	101.4*	0.29	<0.01	0.38	<0.01	<0.01
8-mm screen	101.4*	100.1	98.9*	97.2*	0.52	0.74	0.66	<0.01	0.76
4-mm screen	101.5*	100.6*	100.3*	100.4*	0.14	<0.01	0.22	<0.01	<0.01
1.18-mm screen	87.8*	95.5*	98.2*	99.2*	1.16	<0.01	0.03	<0.01	0.01
Pan	80.5*	94.6*	99.4	100.5	1.30	<0.01	0.04	<0.01	<0.01

[a]Sorting index was calculated as the actual intake of retained particles on each screen divided by the predicted intake (Leonardi and Armentano 2003).

[b]Samples were collected four times during the study, week was analyzed as a repeated measure (data not presented). The interaction between treatment and week was also analyzed. The interaction ($P < 0.05$) was only significant for the pan as the CON treatment sorting index generally reduced with advancing days on feed (Figure 1).

*Indicates difference from 100 ($P \leq 0.05$) using a two-tailed *t*-test.

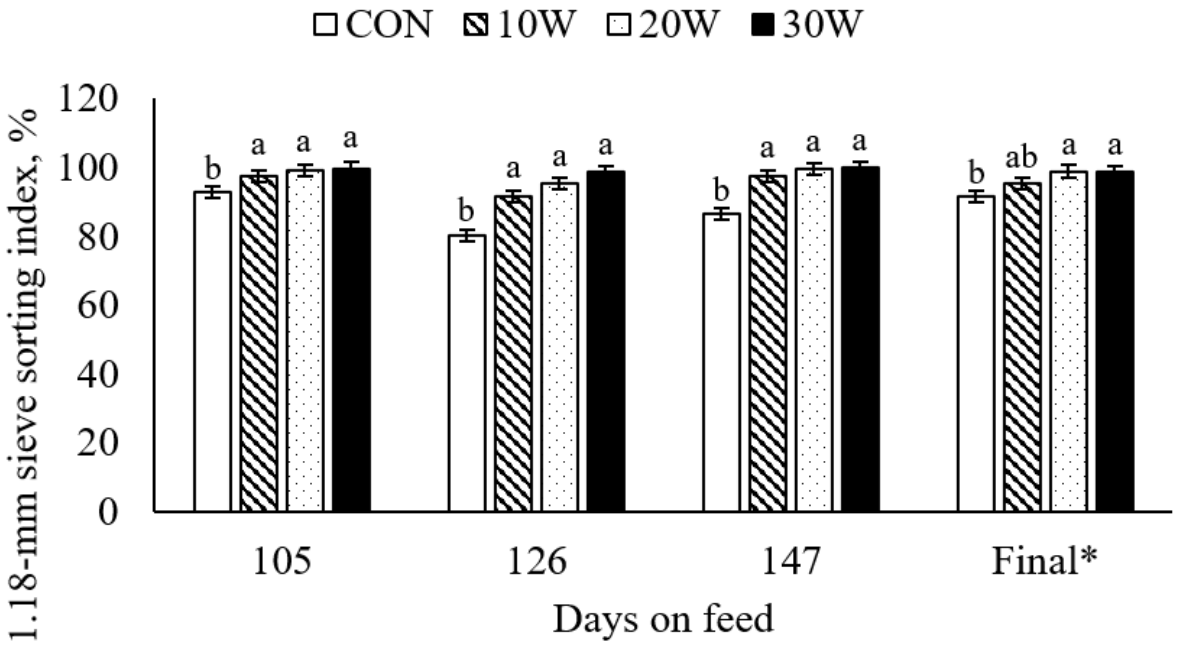

Figure 4.1. *Sorting index values for the treatment × week interaction for particles retained on the 1.18-mm sieve on the Penn State Particle Separator (Spectrum Educational Supplies Ltd., Newmarket, ON, Canada) for diets with 0% (CON), 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain as added water.* ^{a,b,c,d,e}*Different superscripts denote means that differ (P < 0.05) among treatments within each time point.**Final indicates the final day that the steers were in their pen (days on feed = 153, 160, 167, 174, and 181) and averaged per treatment.

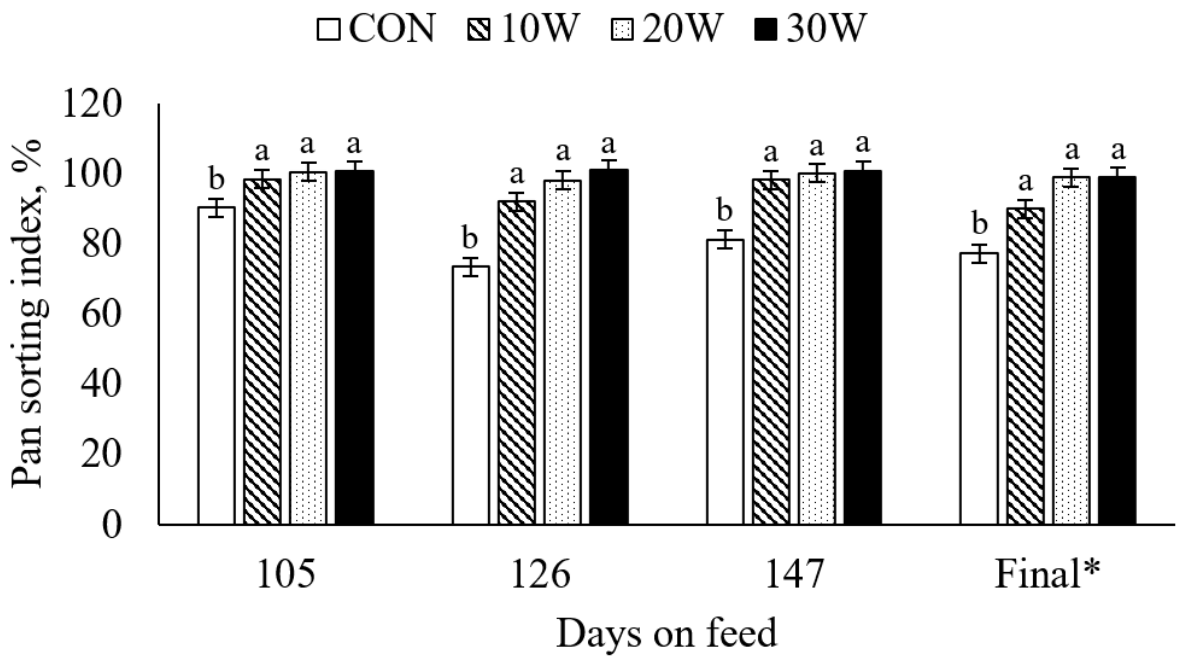

Figure 4.2 Sorting index values for the treatment × week interaction for particles retained on the pan *of the Penn State Particle Separator (Spectrum Educational Supplies Ltd., Newmarket, ON, Canada) for diets with 0% (CON), 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain as added water.* ^{a,b,c,d,e}*Different superscripts denote means that differ (P < 0.05) among treatments within each time point.* *Final indicates the final day that the steers were in their pen (days on feed = 153, 160, 167, 174, and 181) and averaged per treatment.

Table 4.5. Carcass characteristics of steers fed a barley-based finishing diet with 0% (CON), 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain as added water.

						P-value	
Variable	CON	10W	20W	30W	SEM	Linear	Quadratic
Hot carcass weight, kg	354	354	354	357	8.3	0.75	0.76
Hot carcass weight standard deviation (SD), kg	18.2	14.5	13.6	19.4	3.71	0.85	0.17
Dressing percentage, %	61.31	60.86	61.39	60.88	0.305	0.58	0.92
Dressing percentage SD, %	0.964	1.279	1.087	1.196	0.1466	0.44	0.48
Hanging tender, kg	1.4	1.4	1.4	1.4	0.05	0.20	0.78
Hanging tender SD, kg	0.17	0.13	0.18	0.15	0.029	0.79	0.85
Kidney fat, kg	8.8	8.9	9.1	9.7	0.40	0.08	0.46
Kidney fat SD, kg	1.67	1.59	1.87	1.92	0.256	0.38	0.81
Pelvic fat, kg	1.1	1.1	1.1	1.1	0.06	0.84	0.63
Pelvic fat SD, kg	0.22	0.24	0.26	0.24	0.039	0.60	0.62
Heart fat, kg	1.2	1.3	1.3	1.3	0.07	0.29	0.56
Heart fat SD, kg	0.35	0.34	0.29	0.39	0.057	0.81	0.33
Total kidney, pelvic, heart fat, kg	11.1	11.3	11.5	12.1	0.46	0.11	0.67
Total kidney, pelvic, heart fat SD, kg	3.19	3.25	3.30	3.45	0.108	0.10	0.71
Cold carcass weight, kg	348	348	348	351	8.2	0.73	0.76
Cold carcass weight SD, kg	17.8	13.6	13.2	19.0	3.73	0.84	0.16
Shrink loss, %	1.60	1.56	1.52	1.56	0.033	0.30	0.23
Shrink loss SD, %	0.188	0.150	0.150	0.182	0.0257	0.88	0.19
Backfat thickness, mm	10.9	10.4	10.6	10.6	0.45	0.63	0.47
Backfat thickness SD, mm	3.48	2.56	3.00	2.72	0.453	0.30	0.42
Ribeye area, cm^2	91.8	92.5	92.0	95.3	2.15	0.15	0.38
Ribeye area SD, cm^2	5.46	7.72	7.56	7.47	1.002	0.20	0.25
CBGA marbling[a]	414.7	416.2	410.3	407.5	10.49	0.56	0.83
CBGA marbling SD	63.13	58.48	39.70	46.19	7.317	0.05	0.45
Retail cut yield, %	51.10	51.23	51.11	51.11	0.227	0.82	0.51

Table 4.6. (continued). Carcass characteristics of steers fed barley-based finishing diet with 0% (CON), 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain as added water.

						P-value	
Variable	CON	10W	20W	30W	SEM	Linear	Quadratic
Retail cut yield SD, %	1.395	1.196	1.331	1.269	0.2263	0.76	0.70
Rumen epithelial damage, cm^2	629.2	840.7	741.8	812.4	101.58	0.25	0.42
Rumen epithelial damage SD, cm^2	283.12	390.03	376.72	345.14	53.407	0.48	0.21

[a]According to the United States Department of Agriculture were 200 to 299 = trace; 300 to 399 = slight; 400 to 499 = small; 500 to 599 = modest; and 600 to 699 = moderate.

to linearly increase with increasing water addition ($P = 0.08$). The addition of water did not affect the SD for any of the organ fat weights ($P \geq 0.33$). When added together, there was no effect of dietary water addition on KPH fat ($P = 0.11$), but there was a linear tendency for an increase in the variability within a pen with the addition of water to the TMR ($P = 0.10$). Backfat thickness and REA scores were not affected by water addition ($P \geq 0.15$), and there was no effect of water addition on the SD for these measures within pens ($P \geq 0.20$). Marbling score was not affected by the addition of water ($P \geq 0.56$). However, increasing water addition linearly reduced the SD for marbling scores within a pen ($P = 0.05$). The surface area of ruminal epithelial damage was not affected by the addition of water ($P \geq 0.25$). Similarly, there was no effect on the SD among animals in a pen for ruminal epithelial damage ($P \geq 0.21$).

Fat tissue predictions from DEXA for all primal cuts and total carcass fat percentages were not affected by water addition ($P \geq 0.11$; Table 4.6.), except for the shank, where a linear decrease in fat was detected as water addition increased ($P = 0.04$). Similarly, the lean tissue estimation for all primal cuts and total carcass lean percentage were not affected by water addition ($P \geq 0.17$).

All carcasses graded either AA or AAA, and the proportion of each grade was not affected by water addition to the TMR ($P \geq 0.49$; Table 4.7.). The frequency of steers with yield grades 1 to 4 was also not affected by water addition ($P \geq 0.47$). The frequency of steers with clear, minor and severe liver scores were not affected by the addition of water to the TMR ($P \geq 0.38$).

Table 4.7. Dual energy x-ray absorptiometry (DEXA) values of fat and learn percent for primal cuts from steers fed a barley-based finishing diet with 0% (CON), 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain as added water.

						P-value	
Variable	CON	10W	20W	30W	SEM	Linear	Quadratic
Fat, %							
Brisket	42.73	42.25	42.47	41.60	1.090	0.48	0.86
Chuck	25.20	24.73	24.48	24.33	0.419	0.12	0.72
Flank	51.34	50.41	51.02	51.19	0.685	0.95	0.39
Loin	27.32	26.38	26.52	26.46	0.514	0.26	0.39
Plate	41.55	41.09	40.98	40.82	0.555	0.32	0.78
Rib	32.54	31.64	31.29	31.33	0.641	0.16	0.47
Round	17.22	16.55	16.53	16.42	0.337	0.11	0.41
Shank	13.28	13.21	12.62	12.44	0.294	0.04	0.86
Total	27.37	26.74	26.65	26.46	0.451	0.13	0.62
Lean, %							
Brisket	46.95	47.09	46.63	46.90	1.099	0.90	0.95
Chuck	62.15	62.33	62.43	62.50	0.362	0.43	0.88
Flank	47.88	48.86	48.22	47.98	0.684	0.89	0.34
Loin	57.49	58.01	57.98	57.85	0.472	0.56	0.48
Plate	45.36	46.09	46.02	45.53	0.459	0.79	0.17
Rib	51.81	52.17	52.58	52.34	0.615	0.41	0.61
Round	66.81	67.31	67.25	67.08	0.303	0.54	0.29
Shank	48.05	48.13	48.37	48.11	0.145	0.53	0.26
Total	58.20	58.62	58.64	58.53	0.404	0.51	0.49

Table 4.8. Categorical data for liver score, quality grade, and yield grades from steers fed a barley-based finishing diet with 0% (CON), 10% (10W), 20% (20W), or 30% (30W) of the weight of the barley grain as added water.

					P-value	
Variable	CON	10W	20W	30W	Linear	Quadratic
Quality grade						
AA, % of steers	40.00	40.00	36.67	30.00		
AAA, % of steers	60.00	60.00	63.33	70.00		
Odds ratio	1.000	1.000	0.868	0.643	0.49	0.74
95% lower confidence limit		0.298	0.135	0.163		
95% upper confidence limit		3.359	5.599	2.535		
Yield grade						
YG1, % of steers	3.33	6.67	10.00	6.67		
YG2, % of steers	73.33	60.00	66.67	66.67		
YG3, % of steers	20.00	33.33	23.33	26.67		
YG4, % of steers	3.33	0.00	0.00	0.00		
Odds ratio	1.000	0.763	1.311	1.009	0.73	0.47
95% lower confidence limit		0.317	0.521	0.343		
95% upper confidence limit		1.836	3.297	2.971		
Liver score[a]						
Clear, % of steers	46.67	43.33	63.33	50.00		
Minor, % of steers	13.33	13.33	6.67	13.33		
Severe, % of steers	40.00	43.33	30.00	36.67		
Odds ratio	1.000	0.869	1.829	1.139	0.38	0.65
95% lower confidence limit		0.238	0.562	0.399		
95% upper confidence limit		3.171	5.950	3.254		

[a]Liver scores were classified as clear, minor, or severe as adapted from Brown and Lawrence (2010).

4.5. DISCUSSION

4.5.1. Effect of water addition on feed sorting behaviour

In partial support of the hypothesis, the addition of water altered the pen-level sorting behaviour. The general trend was that the sorting index become closer to 100% (indicating no sorting) for particles retained on the 19-, 4-, 1.18-mm sieves, and the pan, as water inclusion increased. Specifically, particles on the pan were not different from 100% for both the 20W and 30W treatments indicating that sorting was effectively prevented. These results support previous research on dairy cattle (Leonardi et al. 2005; Felton and DeVries 2010; DeVries and Gill 2012) and results from Chapter 3.

Optimal water addition rates were calculated using the second derivative for the sorting index values exhibiting a quadratic response with water inclusion rates of 22.0% being optimal to minimize sorting on the 19-mm sieve and 21.7% being optimal to minimize sorting on the 4-mm sieve. The mean water addition to minimize sorting equated to 21.9%. Although the pan and the 1.18-mm sieve were excluded from this average due the treatment × week interaction effect, the optimal rate for minimizing sorting on the 1.18-mm sieve was calculated at 26.2% and pan was calculated at 24.9%, which are in a similar range as observed for the other sieves. The changes in sorting behaviour are likely based on the binding of small particles to larger ones (Miller-Cushon and DeVries 2009). Although not directly measured in this study, the ability of water to promote adherence of small particles to larger ones is well-documented (Leonardi et al. 2005; Felton and DeVries 2010; DeVries and Gill 2012). For example, Leonardi et al. (2005) added water to a dairy TMR as the only dietary change and observed decreased sorting. This concept for feedlot diets was validated in the metabolism study described in Chapter 3. The current study's findings support these earlier studies, indicating that changes in the particle size of the refused TMR are influenced by dietary water addition.

When evaluating feeding behaviour of feedlot cattle, much emphasis is placed on pen-level DMI trends over time (Gibb 2007; Silvestre et al. 2023) and bunk management (Schwartzkopf-Genswein et al. 2003; Smock et al. 2021), while the actual eating and sorting behaviour of the cattle receives less attention. In contrast, feed sorting behaviours are commonly examined in dairy studies (Miller-Cushon and DeVries 2009, 2017b; Felton and DeVries 2010). Feed sorting can be viewed both positively and negatively as cattle may select particle fractions

to mitigate digestive upset (Greter and DeVries 2011; Miller-Cushon and DeVries 2017b) but may also lead to greater variation in the diet available for cohorts in the same pen. Dairy and feedlot cattle have been documented to sort for larger particle sizes in the TMR in response to ruminal acidosis (DeVries et al. 2008; Marchesini et al. 2013). Preventing sorting and maintaining a consistent intake may be a strategy to promote less variability in growth (Miller-Cushon and DeVries 2017a, 2017b) and theoretically, carcass characteristics within a pen. While feed sorting behaviour is frequently overlooked in feedlots, recent studies have confirmed that feed sorting contributes to variable nutrient intake (Custodio et al. 2016; Dykier et al. 2019). The current study contributes to the evidence that feedlot cattle do exhibit sorting behaviours in pen feeding settings.

4.5.2. Effect of water addition on growth performance

Despite differences for dietary sorting, there were no responses for the measured growth, G:F, and most carcass attributes. The lack of differences suggests that altering DM content of the diet did not affect the overall nutrient intake or utilization. This finding aligns with Dykier et al. (2019) who also reported that steers sorted to consume a different diet than what was offered, yet there was no effect on intake energy, digestible energy, or DM digestibility. Similar results have been reported in dairy cattle, where adding water to the TMR either maintained (Leonardi et al. 2005) or reduced DMI without affecting milk production (Miller-Cushon and DeVries 2009; Fish and DeVries 2012). In studies where a reduction in DMI was observed, it was linked to an increase in temperature of the TMR throughout the day, leading to spoilage and unpalatable feed (Miller-Cushon and DeVries 2009; Felton and DeVries 2010). In the current study, feed spoilage was unlikely due to the ambient outdoor temperature being around or below freezing for most of the study. Additionally, the feed was likely not wet enough for rapid spoilage, with the wettest diet having a DM concentration of 65%, compared to dairy diets with a TMR around 48 to 58% DM that experienced spoilage (Miller-Cushon and DeVries 2009; Felton and DeVries 2010).

The lack of growth responses from added water may be in part due to the relatively low extent of barley grain processing. Barley was processed to a mean PI of 84.2 ± 3.4% and had a relatively low proportion of fine particles (particles < 1.18 mm; 2.1 ± 1.0%,). Previous studies recommended barley be processed to levels below 75% PI and to avoid fines exceeding 3% (Mathison et al. 1997; Beauchemin et al. 2001). Adequately processed barley increases the total

ruminal SCFA concentration, reduces ruminal pH, increases microbial protein synthesis, and can increase ADG and G:F responses for feedlot cattle (Beauchemin et al. 2001; Dehghan et al. 2007; Ran et al. 2021). Additionally, with the greater than recommended PI and low proportion of fine particles in the present study, it is possible that the lack of observed performance differences among treatments is due to poor utilization of the barley grain, as indicated by the high fecal starch concentration (Jancewicz et al. 2017a), and fewer small particles at risk of inducing digestive upset.

4.5.3. Effect of water addition on carcass characteristics

While carcass characteristics were generally unaffected, there were tendencies for an increase in the amount of kidney fat deposited and the variability in total KPH within a pen as the amount of added water in the TMR increased. This increase in kidney fat may indicate that cattle were depositing more internal fat as a result of consuming a higher energy diet, due to the inability to sort back fine particles. However, this response was only a tendency, and further research is needed to confirm if this is a repeatable response.

Marbling score was not affected, but there was a linear reduction in the variability among pen-mates for marbling score with increasing water addition. The degree of marbling is one of the most important characteristics of meat quality, as it is one of the highest valued characteristics and it influences purchasing decisions of consumers (Lee et al. 2018). Variability among pen-mates presents a significant challenge for the beef industry, as it reduces uniformity and consistency in finished beef carcasses (National Cattleman's Beef Association, 2017), which ultimately impacts feedlot profitability. Minimizing this variability through feeding management may enhance carcass uniformity in a pen setting, improving both quality for consumers and profitability for feedlots. Additionally, if feedlots can more adequately predict the carcass outcomes of cattle and expect more consistent grades, it may change how cattle are marketed with producers choosing to market based on projected quality as opposed to carcass weight. It is possible that adding water promoted a more consistent nutrient consumption by reducing sorting of the TMR, thereby resulting in more consistent deposition of intra-muscular fat, despite the lack of effect for growth responses. Future research is needed to confirm is these results are repeatable.

The DEXA results generally showed no response in fat and lean percentage for the primal cuts. However, there was a reduction in shank fat percentage with the addition of water to the TMR. Its important to note that the correlation coefficient for shank fat reported by López-Campos et al. (2018) is much lower ($r^2 = 0.813$) than the correlations for fat and lean percentages for the other primal cuts ($r^2 = 0.943$ to 0.992). Therefore, the response for shank fat warrants verification using a traditional cut-out approach.

Rumen epithelial damage was quantified as the total surface area of papillae erosion, regardless of the stage the damage (healed versus active lesions). This method provided a quantitative measure of damage rather than relying on a subjective grading system. Notably, every steer in this study exhibited some degree of epithelial damage. However, as no other studies have quantified rumen damage in this manner, it is not possible to assess whether the observations are consistent under differing production and feeding management systems. Furthermore, it is uncertain whether the damage occurred solely during the study or prior to its onset, particularly considering that most of the detected damage appeared to be old and healed into scar tissue. Similar uncertainty regarding the origin of rumen damage has been highlighted in other studies where extensive epithelial damage was observed (Kinley et al. 2024).

Livers were scored for abscess severity and across all treatments, approximately half of the steers had minor or severe liver abscesses. The high prevalence of liver abscesses is somewhat unexpected given the low extent of barley processing in the diets. However, this may be linked to the observed ruminal epithelial damage, as damaged areas may allow bacteria to cross the rumen wall, enter the portal bloodstream, and contribute to liver abscess formation (Foreman 2023). Again, timing for the onset of liver abscess formation is not known and it is not possible to attribute these outcomes solely to the treatments in the present study. Despite the high incidence of liver abscesses in this study, these findings align with recent studies evaluating liver abscess prevalence in feedlot cattle fed barley-based finishing diets (Nixdorff et al. 2020, Paterson et al. 2024).

4.6. CONCLUSION

This study partially confirmed the hypothesis that adding water to a TMR fed to finishing cattle binds fine particles to the larger particles, reducing pen-level sorting for finishing steers, with an optimal water addition equating to 21.9% of the barley grain weight. Further evidence to support reduced sorting included a linear reduction in the SD for the marbling score with increasing water inclusion. However, contrary to the hypothesis, there was no response for growth or carcass characteristics, which may be due to the use of inadequately processed barley. The results of this study suggest that adding water to barley-based finishing diets may reduce sorting and variability among pen-mates for marbling scores without affecting performance.

5.0. GENERAL DISCUSSION

The primary objective of the metabolism (Chapter 3) and feedlot (Chapter 4) studies presented in this thesis was to evaluate the impact of adding water to barley-based feedlot diets on digestion, nutrient utilization, growth performance, and carcass characteristics. I hypothesized that incorporating water into the TMR would bind the ingredients during mixing, reducing the ability of cattle to sort the diet, and thereby enhance growth and reduce variation in responses within pen-mates.

5.1. Comparison of Study Findings

Both studies were designed to impose the same treatments. The results from both studies supported the hypothesis that adding water to the feedlot TMR binds ingredients together during mixing. In Chapter 3, the particle size distribution of the diet was measured using the PSPS, and results confirmed that the addition of water decreased the proportion of particles retained on the 1.18-mm sieve and the pan. This response implies that the fine particles were bound with larger particles that were retained on the larger sieves. As water addition altered particle size distribution, the CON diet was used to calculate the sorting index by comparing the refusal particle size distribution and quantity refused. This same approach was used in Chapter 4 to calculate the sorting index values. However, the particle size distribution of each diet use in Chapter 4 was not measured due to the challenges of collecting a representative sample of the TMR. The binding effect arising from water addition led to a decrease in the sorting index values in both Chapter 3 and Chapter 4 when compared to the CON diet. The reduction in diet sorting observed in both studies is consistent with findings from previous research with beef and dairy cattle (Leonardi and Armentano 2003; Dykier et al. 2019; Denißen et al. 2021) reporting that adding water to the TMR reduces diet sorting and potentially altering feed intake behaviour.

A notable difference observed between the two studies was the differing effect on DMI. In Chapter 3, there was a linear increase in DMI with increasing water content in the TMR. However, in Chapter 4, no differences in DMI were detected among treatments. This difference may be due to differences in barley processing between the two studies. In Chapter 3, a single batch of barley was used and was processed to generate a substantial proportion of fine particles. The resulting PI was 62.2 ± 2.1% and the percentage fines were 3.2 ± 1.0%. Although the

percentage fines were not as high as anticipated given the low PI, it was still above the recommended maximum of 3% (Mathison 2000), but below the industry adopted 5% maximum. In contrast, the barley used in Chapter 4 was sourced from a commercial feed-mill and involved multiple batches with varying degrees of processing, resulting in a higher PI of 84.2 ± 3.4% and percentage fines were of 2.1 ± 1.0%, which is drastically less processed than in Chapter 3. A study by Zinn (1993) found that as the flaking density of the barley became thinner, there was a corresponding increase in DMI. Another study by Yang et al. (2000) compared barley processed to a PI of 81% versus 64% and observed an increase in DMI with more severe processing, although this study was conducted using Holstein cows fed lactating diet. This aligns with findings by Ran et al. (2021) that compared different PI of barley processing of 65, 75, and 85%, and reported that lower digestibility of DM and OM was observed for the 85% PI and increased for both the 65% and 75% PI treatments. In my studies, it is possible that using the same PI in both experiments would have resulted in a more consistent DMI response, as the passage rate and digestibility may have been more consistent among studies. However, it is important to note that in Chapter 3, even though the steers were experiencing ruminal acidosis (as indicated by the duration of low ruminal pH and high ruminal LPS concentration), they increased their DMI. Although a metabolism study is not reflective of feeding cattle in large groups, this response is encouraging for feedlot producers, as a higher DMI typically leads to a higher ADG.

5.2. Practical applications of this research

Adding water to feedlot diets can be a valuable management strategy for feedlot operators. The findings from these studies demonstrate that incorporating water into the feedlot TMR alters the particle size distribution and affects how cattle sort the TMR. Feedlot nutritionists can use water to encourage nutrient intake that more closely matches the nutrients provided, potentially improving ADG projections, and leading to more consistent growth and reduced variability among pen-mates. While there was limited evidence of reduced variability, a reduction in the variation for the marbling score among pen-mates was detected, providing at least preliminary support for reduced variation. The minimal effects in response to the increasing water inclusion may be attributed to the low extent of barley processing (as described above) and the stocking rate of the pens. Unlike typical commercial settings, Chapter 4 had only 6 animals per pen yielding a stocking density of 37 m^2/steer and feed bunk space of approximately 1

m/steer, which does not reflect industry-standard stocking rates of 15 m^2/steer and feed bunk space of 0.3 m/steer, and associated competition pressures (Beef Cattle Research Council 2024; Schwartzkopf-Genswein et al. 2003; Pritchard and Bruns 2003). Additionally, cattle were fed once daily, and refusals were managed under *ad-libitum* feeding conditions to ensure there were refusals for analysis. In contrast, commercial feedlots often feed multiple times per day and implement slick-bunk management, where the bunks are nearly empty by the morning, ensuring cattle consume all the feed provided (Pritchard and Bruns 2003). The feeding management differences between a commercial feedlot and the studies in this thesis means that, in Chapter 4, steers could spend more time sorting the diet to their preferences rather than consuming what was immediately available.

When scaling up the results from the small-scale research studies to a commercial feedlot, one of the major considerations is the amount of water required. In both Chapter 3 and Chapter 4, the differences between 20W and 30W inclusions were much smaller and more consistent compared to the differences between the CON and 10W treatments and the 20W results. To maximize efficiency while achieving a good binding response, the optimal amount of water likely falls between 20% and 30% of the barley grain weight. In Chapter 3, the responses for the sorting index were linear, indicating that the optimal amount of added water exceeded the 30W treatment. However, based on the results from Chapter 4, the optimal amount of water addition is 21.9% relative to the weight of the barley grain for a barley-based finishing TMR. A typical feedlot diet may consist of 88% barley, 10% silage, and 2% mineral and vitamin premix. The average load size for a finishing diet is approximately 11,000 kg (S. Theissen, personal communication, 2024). The amount of water needed can be calculated using the following formula. Depending on the size of the load and the amount of water required, there is a large range of water needed to be included in the TMR (Table 5.1.).

$$Water\ needed = (weight\ of\ total\ TMR * barley\ \%\ inlcusion) * water\ \%\ inclusion$$

For example:

$$Water\ needed = (11{,}000\ kg * 88\%) * 21.9\%$$

$$Water\ needed = (9{,}680\ kg) * 21.9\%$$

$$Water\ needed = 2{,}120\ kg\ or\ 2{,}120\ L\ or\ 466.3\ gal\ PER\ LOAD$$

Table 5.1. Water addition (kg) required for a total mixed ration based on load size and targeted water inclusion rate, for a barley-based finishing feedlot diet containing 88% barley grain (DM basis).

	Targeted water inclusion rate, %					
Load size, kg	20	22	24	26	28	30
8000	1408	1549	1690	1830	1971	2112
9000	1584	1742	1901	2059	2218	2376
10000	1760	1936	2112	2288	2464	2640
11000	1936	2130	2323	2517	2710	2904
12000	2112	2323	2534	2746	2957	3168
13000	2288	2517	2746	2975	3203	3432
14000	2464	2710	2957	3203	3450	3696
15000	2640	2904	3168	3432	3696	3960

An important consideration is that 21.9% water inclusion was the optimal amount for the specific diet conditions used in the study. A more practical recommendation for feedlots would be to base water inclusion on DM content of the diet. Using this approach, feedlots can determine the DM of their current diet based on the proportion of the ingredients used and then adjust the water addition to achieve the desired DM content. In Chapter 4, adding 21.9% water resulted in an optimal DM content of 68.7%. Anecdotally, during discussions at scientific conferences, nutritionists commonly recommend adding moisture to finishing feedlot diets to target a DM content of 68%. This research supports that industry recommendation.

In most cases, water is relatively low-cost for feedlots, particularly if they have access to their own water source. Even if the water needs to be purchased, the cost is generally negligible (S. Theissen, personal communication, 2024). However, the logistics of incorporating large quantities of water into the TMR can be challenging. A feedlot needs a high-capacity water source capable of quickly distributing water into the TMR; a simple water faucet may not be sufficient. Table 5.2. shows the time required to add 21.9% water based on different water dispensing rates. Using a low-capacity water dispensing rate source (ex. 1 kg/s) would take a very long time and would not be feasible as the slow fill rate would harm feedlot efficiency.

Most feedlots have a water source at the mill, especially if they use a flush system in the micro-mineral machine, but additional infrastructure may be necessary to support a high flow water distribution system. Another consideration is the mixing time required to properly incorporate the water into the TMR. In Chapter 3, each steer's diet was mixed by hand until it appeared to be evenly distributed, while in Chapter 4, the mixing was 5 minutes per batch. This was adequate for the small batch sizes and conveniently matched the time it took to travel from the water distribution setup to the first bunk. In larger batches, longer mixing times may be necessary, potentially reducing feedlot efficiency due to timing spent waiting for thorough mixing. Finally, the additional wear and tear on equipment must be considered. Water is a heavy ingredient, and when the TMR mixture becomes sticky, it can strain equipment during mixing. Adding 21.9% water to an average finishing diet is projected to add 2.1 mT to the wagon, based on an 11,000 kg load size. This may limit load capacity of the mixer to account for the additional weight of the water, potentially increasing the number of loads required and extending the feeding duration.

Table 5.2. Effect of water dispensing rate and load size on the time required (min) to add 21.9% of barley weight (88% DM) as water to a barley-based finishing diet.

	Water dispensing rate, kg/s			
Load size, kg	1	5	10	15
8,000	25.7	5.1	2.6	1.7
9,000	28.9	5.8	2.9	1.9
10,000	32.1	6.4	3.2	2.1
11,000	35.3	7.1	3.5	2.4
12,000	38.5	7.7	3.9	2.6
13,000	41.8	8.4	4.2	2.8
14,000	45.0	9.0	4.5	3.0
15,000	48.2	9.6	4.8	3.2

5.3. Future research needs

While the findings from these studies provide valuable insights into the effects of adding water to a barley-based feedlot diet, there is still much more to explore in this area. The current body of research on water addition to feedlot diets is limited, and these studies contribute to the growing understanding of this practice. However, these two studies highlight the need for further investigation before this practice can be widely adopted. Future research should consider the following areas:

1. **Large-scale feedlot studies**: Conducting large-scale feedlot studies to assess the impact of stocking density on sorting behaviours and potential reductions in standard deviation among pen-mates on performance and carcass characteristics when sorting ability is reduced.
2. **Optimal water inclusion:** Identifying the optimal water inclusion that effectively reduces sorting behaviours while minimizing the amount of water needed in the TMR.
3. **Interaction of processing severity and water inclusion:** Comparing different levels of barley processing severity and water inclusion to find the most effective combination for feedlot diets.
4. **Water addition during transition phases:** Investigating whether adding water is beneficial during the transition phase when cattle are being introduced to feed, and if it helps in reducing digestive disorders or improves adaptation.
5. **Economic analysis:** Performing a comprehensive economic analysis to evaluate the benefits of adding water to feedlot diets, including whether the reduction in variability within a pen justifies the additional logistical costs associated with water inclusion in the TMR.

By addressing these areas, future research can provide clearer guidance on the practical application of water addition in feedlot diets and help optimize feeding strategies for better animal performance and economic efficiency.

6.0. GENERAL CONCLUSION

In this thesis, I hypothesized that adding water to a barley-based feedlot diet for finishing cattle would reduce the potential for sorting of the diet. This, in turn, was expected to mitigate the risk of digestive upset by promoting a consistent intake of nutrients throughout the day. It was further hypothesized that reducing sorting would lead to more consistent growth and carcass characteristics among pen-mates, as all animals within a pen would consume a more similar diet, regardless of their position at the feed bunk. However, potential drawbacks of this management technique include the increased risk of digestive upsets, such as bloat and ruminal acidosis, due to the increased consumption of fine particles and inability to sort the diet for longer particles.

The results of this research demonstrated that adding water to a barley-based feedlot diet effectively bound fine particles to larger particles, thereby inhibiting sorting of small feed particles by steers. In Chapter 3, which focused on nutrient digestion, there were no differences in the overall diet digestibility or starch passage rate out of the rumen across the four treatment diets, but there was a decrease in mean and maximum ruminal pH, which may have been from an increase in DMI and an increase in fine particle consumption. In Chapter 4, a feedlot pen study, there was no impact of the treatment diets on growth performance or carcass characteristics. However, a reduction in pen variability for marbling score was observed as water was added to the diet.

In conclusion, although minimal changes were observed in digestion, growth performance, and carcass characteristics, the addition of water to the feedlot diet did not adversely affect the cattle. Thus, the results partially support my hypothesis, suggesting that adding water to a barley-based feedlot diet can be an effective strategy to reduce sorting, at the potential expense of inducing ruminal acidosis. However, the anticipated improvements in growth performance and carcass characteristics were not observed, although this response may be due to the coarsely dry-rolled barley grain that was used. Future research on a larger scale is recommended to determine if these results are repeatable and practical for broader feedlot implementation.

7.0. LITERATURE CITED

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