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Abstract

This study compared dry-rolled and tempered hybrid rye when processed to a coarse or fine severity on dry matter intake (DMI), ruminal fermentation, and apparent total tract nutrient digestibility for beef cattle. Eight ruminally cannulated Simmental heifers (327 ± 33.1 kg, mean $\pm$ SD) were used in a replicated 4×4 Latin square (21-day periods with 16 days for adaptation and 5 d collection) balanced for carry-over effects with a 2×2 factorial arrangement of treatments. Feeding tempered rye increased ($P = 0.01$) DMI when compared to dry-rolled rye, but there was no effect of processing severity. Cattle fed dry-rolled rye had a greater ($P = 0.04$) area that pH was <5.5 when compared to those fed tempered rye. Feeding dry-rolled rye increased dry matter digestibility ($P = 0.02$) and crude protein digestibility ($P = 0.01$) when compared to tempered rye, and there was a greater effect to increase total tract starch digestibility with increasing severity of processing for tempering than for dry rolling (interaction, $P = 0.03$). In conclusion, tempered hybrid rye processed to a fine severity may result in similar total tract starch digestibility to dry-rolled hybrid rye without the marked reductions in DMI and ruminal pH.

Key words: processing severity, dry-rolled, tempered

Résumé

Cette étude a comparé un hybride de seigle aplati à sec et conditionné, lorsque transformé selon une sévérité brute ou fine, et les effets sur la consommation des matières sèches (DMI — « dry matter intake »), la fermentation dans le rumen, et la digestibilité apparente du tractus total des éléments nutritifs auprès des bovins de boucherie. Huit génisses Simmental canulées dans le rumen ($327 \pm 33,1$ kg, moyenne $\pm$ écart type [SD — « standard deviation »]) ont été utilisées dans un carré latin 4×4 répliqué (périodes de 21 jours avec 16 jours pour adaptation et 5 jours de collecte) équilibré pour les effets de report avec un arrangement factoriel 2×2 des traitements. L'alimentation au seigle conditionné a augmenté ($P = 0,01$) le DMI par rapport au seigle aplati à sec, mais il n'y avait pas d'effet de la sévérité de transformation. Les bovins ayant reçu le seigle aplati à sec avaient une plus grande ($P = 0,04$) surface dont le pH était inférieur à 5,5 par rapport au seigle conditionné. Nourrir les bovins de seigle aplati à sec a augmenté la digestibilité des matières sèches ($P = 0,02$) et la digestibilité des protéines brutes ($P = 0,01$) par rapport au seigle conditionné, et il y avait un plus grand effet d'augmentation de la digestibilité de l'amidon dans le tractus total avec l'augmentation de la sévérité de transformation pour le seigle conditionné par rapport au seigle aplati à sec (interaction, $P = 0,03$). En conclusion, le seigle hybride conditionné transformé à sévérité fine peut se traduire par une digestibilité de l'amidon dans le tractus total semblable à celle du seigle hybride aplati à sec sans les réductions marquées de DMI et de pH dans le rumen. [Traduit par la Rédaction]

Mots-clés : sévérité de transformation, aplati à sec, conditionné

Introduction

Rye is an important cereal crop in North America and Europe principally due to its good overwintering ability, adaptability to various climatic conditions, drought tolerance, and is an attractive alternative to growing barley, wheat, or sorghum, especially on poor soil (Geiger and Miedaner 2009; Arendt and Zangnini 2013). Rye offers several benefits that warrant consideration as it can be grazed and harvested for forage, grain, and straw, and the winter cover provided may reduce soil erosion (Kaspar et al. 2001) without depletion of

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soil organic matter (Kaspar et al. 2006). However, rye grain has not been traditionally used as a cereal grain for finishing cattle, possibly due to high risk for ergot contamination and the negative effects of ergot on feed intake and gain (Matsushima 1979). Newer hybrid rye germplasms have become available in North America and these varieties have lesser ergot incidence compared to open-pollinated rye varieties (Hansen et al. 2004) opening the possibility of utilizing hybrid rye to a greater extent in diets fed to feedlot cattle.

Processing characteristics can have a marked impact on ruminal starch availability of small grains with an inherently rapid starch degradation rate. Overprocessing may increase the risk for ruminal acidosis (Plaizier et al. 2009; Krieg et al. 2017), while underprocessing results in suboptimal starch digestibility (Jancewicz et al. 2017). Rajtar et al. (2020) compared whole, crushed, or ground hybrid rye kernels using in situ and in vitro incubations and reported that increasing severity of processing markedly increased the rapidly degradable fraction of starch, with that proportion being more than two times greater for rye than for corn grain independent of processing severity. Such processing changes resulted in a marked increase in the estimated ruminal degradability without impacting the predicted total tract digestibility of starch. Published studies evaluating hybrid rye as a cereal grain for cattle have utilized dry-rolled rye processed to a processing index of 78% (Rusche et al. 2020) or unprocessed rye (Buckhaus et al. 2021), but questions remain about how processing method and severity may be optimized for rye grain inclusion in diets for finishing cattle. For other small cereal grains with rapid starch digestion, like barley, studies have reported a positive effect of increasing the severity of dry rolling on dry matter (DM) digestibility (Nicholson et al. 1971; Ørskov et al. 1978; Mathison et al. 1991). Moreover, tempering has been reported to reduce the production of fine particles when processed using the same gap width as dry-rolled barley (Nixdorff et al. 2020). The reduction of fines with tempering allows for a greater processing severity than dry-rolled barley resulting in improved performance of cattle (Hinman and Combs 1983; Yang et al. 1996; Wang et al. 2003). Given that dry rolling may increase fine particles during processing (Dehghan-banadaky et al. 2007), and that rye is rapidly degraded in the rumen (Benninghoff et al. 2015; Krieg et al. 2017), tempering may serve as a viable processing method to ensure adequate starch degradability without risk for excessive production of fine particles.

The hypothesis was that tempering and decreasing the severity of the processing for hybrid fall rye would increase dry matter intake (DMI) and ruminal pH, and decrease short-chain fatty acid (SCFA) concentration in the rumen with little effect on total tract starch digestibility. Moreover, it was thought that dry rolling hybrid rye would increase particle sorting with heifers selectively avoiding small particles. Thus, this study was designed to evaluate the effect of processing method and severity for hybrid fall rye on DMI and feed sorting, ruminal fermentation, and apparent total tract nutrient digestibility in ruminally cannulated beef heifers.

Materials and methods

All procedures involving the use of cattle in this study were approved by the University of Saskatchewan Animal Research and Ethics Board (protocol number 20190141) prior to completing any research activity and were conducted in accordance with the guidelines of the Canadian Council on Animal Care (Ottawa, ON, Canada).

Animals and experimental design

The study was conducted at the University of Saskatchewan Livestock and Forage Centre of Excellence (Clavet, SK, Canada). Eight Simmental yearling heifers (328 ± 33.1 kg) were purchased from a single source, halter trained, and surgically fit with a 7.6-cm ruminal cannula (model 3C; Bar Diamond Inc., Parma, ID). Approximately 2 weeks post-surgery, sutures were removed, and the 7.6-cm cannula was replaced with a 10-cm cannula (Model 9C; Bar Diamond Inc.). Heifers were housed in individual tie stalls (1 m $\times$ 2 m) fit with water mattresses on the floor, automated water bowls, and an individual feed manger. Heifers were provided access to an outdoor exercise yard daily for approximately 2 h during feed preparation except during sampling periods or in cases of extreme weather (<-30 °C).

Prior to the start of the study, cattle were gradually transitioned (five intermediate diets over 48 days) to a high-grain diet composed of barley silage, barley grain, canola meal, and a barley-based mineral and vitamin supplement. The amount of feed offered during the diet transition was restricted to 2.3% of body weight (BW) on a DM basis. Heifers were abruptly switched to their treatment diet at the start of the study. Abrupt diet transitions were also used at the start of each period.

The study was conducted as a replicated 4 $\times$ 4 Latin square with a 2 $\times$ 2 factorial arrangement of treatments utilizing 21-day periods. Each square had a unique treatment sequence and sequences were balanced for carry-over effects. Diets (Table 1) were formulated using the Beef Cattle Nutrient Requirements Model (NASEM 2016) and included (DM basis) 15% barley silage, 6% of a mineral and vitamin supplement using barley grain as a carrier, 3% dry distillers' grains with solubles, and 76% hybrid rye grain (KWS Bono, FP Genetics, Regina, SK, Canada). The hybrid rye grain was processed using dry rolling or temper-rolling methods with a narrow (0.8 mm) or wide (1.23 mm) roller gap width. The roller mill (Sven-Mill 4, Apollo Machine and Products, Saskatoon, SK, Canada) had two 17.8-cm diameter rollers with 6.3 grooves/cm and a groove depth of 2.4 mm. Scrapers on each roller were used to prevent grooves from plugging. The gap width of the rollers was tested repeatedly for dry-rolled hybrid rye grain until achieving the target densities prior to the start of the study. Once achieved, the roller gap width was documented, and the roller gap remained static for the duration as a single lot of hybrid rye was used for the duration of the study. The same gap widths were used for dry-rolled and temper-rolled grains as described by Nixdorff et al. (2020). For tempered hybrid rye, water was added to achieve a DM of 80%, and the grain was soaked for 24 h prior to rolling. The tempered hybrid rye was processed in batches every 2 days. A single bunker-style pit of

Table 1. Diet ingredients and chemical composition of the method (dry-rolled or tempered) and severity (coarse or fine) of hybrid fall rye processing as a grain source for cattle.

Item	Dry-rolled		Tempered	
	Coarse	Fine	Coarse	Fine
Ingredients (% of DM)				
Rye grain	76.00	76.00	76.00	76.00
Barley silage	15.00	15.00	15.00	15.00
DDGS	3.00	3.00	3.00	3.00
Mineral*	6.00	6.00	6.00	6.00
Nutrient content[†] (% of DM)				
DM (%)	82.28 ± 0.28	82.12 ± 0.29	75.58 ± 0.28	75.36 ± 0.50
Crude protein	14.65 ± 0.26	14.56 ± 0.17	14.78 ± 0.16	14.54 ± 0.06
Neutral detergent fiber	24.48 ± 1.30	22.58 ± 1.78	23.61 ± 0.50	22.85 ± 0.27
Starch	49.43 ± 0.67	49.62 ± 0.66	48.77 ± 0.86	49.40 ± 0.59
Ether extract	1.92 ± 0.31	1.67 ± 0.26	1.80 ± 0.46	1.89 ± 0.38
Ca	0.81 ± 0.01	0.83 ± 0.03	0.82 ± 0.02	0.82 ± 0.01
P	0.33 ± 0.01	0.33 ± 0.02	0.34 ± 0.01	0.33 ± 0.01
NEm[‡] (Mcal/kg)	1.98 ± 0.03	1.98 ± 0.03	1.98 ± 0.02	1.99 ± 0.02
NEg[§] (Mcal/kg)	1.32 ± 0.02	1.33 ± 0.03	1.32 ± 0.02	1.33 ± 0.01
Dietary particle size distribution[∥] (% as is basis)				
>19.0 mm	0.96 ± 0.16	0.96 ± 0.16	0.96 ± 0.16	0.96 ± 0.16
<19.0 to >8.0 mm	6.78 ± 0.73	6.78 ± 0.73	6.78 ± 0.73	6.78 ± 0.73
<8.0 to >4.0 mm	12.59 ± 2.67	12.51 ± 3.48	41.72 ± 2.60	54.27 ± 4.61
<4.0 mm	79.67 ± 2.06	79.75 ± 3.08	50.54 ± 2.78	37.99 ± 5.23

Note: DM, dry matter; NEm, net energy for maintenance; NEg, net energy for gain.
*Mineral supplement: Ca, 11.96%; P, 0.55%; Mg, 2.56%; K, 0.54%; S, 0.13%; Na, 1.37%; Cl, 1.81%; Fe, 516.75 mg/kg; Mn, 70.00 mg/kg; Zn, 285.50 mg/kg; Cu, 350.25 mg/kg; vitamin A, 45 406.71 IU/kg; vitamin D, 7353.313 IU/kg; vitamin E, 1163.689 IU/kg. The final supplement contained 917.69 mg/kg of monensin (Elanco Animal Health, Greenfield, IN, USA) on a DM basis.
[†]Nutrient content is expressed as means ± SD ($n = 4$).
[‡]Net energy for maintenance was calculated from feed samples using the NRC (2001) equations.
[§]Net energy for gain was calculated from feed samples using the NRC (2001) equations.
[∥]Particle size distribution is expressed as means ± SD ($n = 4$).

barley silage was used, and a single lot of all other ingredients was sourced from the Canadian Feed Research Centre (North Battleford, SK, Canada; dry distillers' grains with solubles and vitamin, and mineral supplement).

The resulting severity of processing was measured using a 1.18 mm sieve and a pan from the Penn State Particle Size Separator (Kononoff et al. 2003) to determine the percentage of fine particles. In addition, the processing index (PI) was calculated, in duplicate, by measuring the weight of the processed sample in a 500 mL container and dividing that weight by the weight of the unprocessed sample filling the same container (Beauchemin et al. 2001). The PI (expressed in OM and DM) and percentage of fine particles (<1.18 mm) for each batch processed (dry-rolled coarse, dry-rolled fine, tempered coarse, and tempered fine) were recorded throughout the study.

Kernel characteristics (width, thickness, and length) were determined using 10 randomly selected kernels from each source in each period according to Zinn (1993) and Johnson et al. (2020). Amyloglucosidase reactive soluble starch (AGR) and amylase reactive insoluble starch (ARIS) were analyzed according to Zinn (1990) and Rodríguez et al. (2001). Briefly, dried samples were ground to pass through a 1-mm screen. For AGR, 0.5 g was incubated in an acetate-based (24 mmol/L) buffer solution containing toluene and amyloglucosidase (26

IU/sample; Sigma-Aldrich, Oakville, ON, Canada). Samples were incubated at 39 °C for 4 h with mixing occurring every 20 min. Immediately after incubation, samples were placed in an ice bath for 10 min, 2 mL of a zinc sulfate solution (15% wt/vol) was added, and samples were filtered. To each sample, 4 mL of o-toluidine solution (0.6 mol/L) was added and the amount of glucose released was determined using a photospectrometer at a wavelength of 630 nm. The amount of glucose released was determined using a colorimetric assay. The ARIS was determined using 0.15 g of sample and enzymatic digestion using amyloglucosidase (26 IU/sample), α-amyloglucosidase (240 IU/sample), porcine pancreatin (8 mg/sample), yeast-based lyticase (400 IU/sample), and protease from *Bacillus licheniformis* (2 mg/sample) in a phosphate buffer solution. Samples were incubated at 39 °C for 6 h with mixing occurring every 30 min. After 10 min in an ice bath, 2 mL of zinc sulfate solution was added, and samples were maintained at room temperature for 10 min. Samples were then filtered, 4 mL of o-toluidine solution (0.6 mol/L) was added, heated at 100 °C for 10 min, followed by 5 min in an ice bath, and 10 min at 27 °C. Absorbance was then read at 630 nm. Values for AGR and ARIS were then used in calculations described by Corona et al. (2006). Insoluble reactive starch (IRS, %) was calculated as ((ARIS – AGR)/6), where 6 represents the number of hours of in vitro incubation. Insoluble

starch that was potentially digestible (ISD, %) was calculated as $(100 - \text{AGR}) \times ((\text{IRS})/(\text{IRS} + 0.06))$, where 0.06 represents the passage rate of grain from the rumen as estimated by Ørskov and McDonald (1979). Predicted ruminal starch digestion (PRSD, %) was calculated as $(1.32 \times \text{AGR}) + (0.93 \times \text{ISD})$, with the maximum value set at 100% according to Johnson et al. (2020). In addition, 7 h in vitro starch digestibility was determined at Cumberland Valley Analytical Services (Waynesboro, PA) as described by Johnson et al. (2020).

Throughout the study, heifers were fed to achieve ad libitum intake with fresh feed provided once daily at 09:00 h and were allowed ad libitum access to water. Refusals (targeting 5%–10% relative to the weight of the feed offered) were removed, weighed, and collected daily at 08:00 h. While the amounts of feed offered and refused were recorded daily, data used for statistical analysis were restricted to those measured from day 16 to day 21 of each period. Refusal samples from day 16 to day 21 within each sampling period were composited by heifer proportionally to the amount refused each day. Representative feed ingredients samples of silage (1 kg/d), hybrid rye (0.5 kg/d), dry distillers' grains with solubles (0.5 kg/d), and mineral (0.5 kg/d) were collected daily from day 16 to day 21 at 08:00 h and were composited by ingredient. The hybrid rye samples were collected from each processing treatment and the original unprocessed grain source. Composited feed ingredient and refusal samples were dried in a forced-air oven at 55 °C for 72 h to determine the DM concentration. The DMI was then calculated based on the amount of feed offered and refused when corrected for DM concentration. In addition, silage DM was measured twice weekly, and the DM of all other ingredients was measured once weekly. Dietary feed ingredient inclusion rates (as-fed basis) were updated to reflect most recent DM of ingredients. The dried feed ingredient and refusal samples were ground using a hammer mill to pass through a 1 mm sieve (Christy and Norris Ltd, Chelmsford, UK) and stored until being analyzed. Water was supplied ad libitum.

The particle size distribution of each diet was determined in duplicate using representative 1 L samples of each ingredient with the Penn State Particle Separator (Nasco Education, Fort Atkinson, WI) according to Heinrichs (2013). The particle size separator included sieves with aperture sizes of 19, 8, and 4 mm and a pan; the distributions are reported in Table 1. Particle size distribution of refusals were also determined using the composited refusal sample for each heifer within each period. All particle size measurements were conducted on an as is basis. The sorting index for particles retained on each sieve was calculated as (actual nutrient intake)/(theoretical nutrient intake) $\times$ 100%, as described by Leonardi and Armentano (2003). Particle sorting values equal to 100 indicate no sorting, those <100 indicate selective refusals (sorting against), and those >100 indicate preferential consumption (sorting for).

Ruminal fermentation

Indwelling ruminal pH measurement was initiated on day 17 of each period and proceeded for the subsequent 96 h as described by Penner et al. (2006). Indwelling ruminal pH mea-

surement systems (Dascor, Escondido, CA) were placed in the ventral sac of the rumen and were maintained in that location using 2 kg of weight. The pH systems were programmed to record a measurement every 5 min. Prior to insertion into the rumen and following removal, the pH systems were standardized in pH buffers 7 and 4 at 39 °C. The raw data collected during measurement were transformed from mV recordings to pH using beginning and ending linear regressions derived from the starting and ending standardizations while accounting for drift that was assumed to be linear over time (Penner et al. 2006). The pH values were then used to calculate the minimum, mean, and maximum pH along with the duration and area that pH was <5.5.

Samples of ruminal digesta (250 mL/region) were collected from three regions of the rumen (cranial, central, and caudal) at the ruminal fluid–ruminal mat interface beginning at 07:00 h on day 18 and every 12 h thereafter with a 3 h offset on subsequent days until day 21. The sampling approach resulted in a total of eight samples collected for each heifer that represented every 3 h of a 24 h feeding cycle. The digesta from each region were pooled and samples were strained through two layers of cheesecloth. The resulting ruminal fluid was mixed, and two 10 mL aliquots were collected. One 10 mL sample was preserved in 2 mL of metaphosphoric acid (25% wt/vol) for measurement of SCFA concentration (Khorasani et al. 1996) and the other was preserved in 2 mL of 1% sulfuric acid for ammonia-N analysis (Broderick and Kang 1980). These samples were sealed and stored at −20 °C until analysis.

Apparent total tract digestibility and chemical analysis

Titanium dioxide (TiO_2) was used as a marker to predict fecal output and was included at 0.2% of dietary DM from day 13 to day 20 of each period. Fecal samples (200 g) were collected from the rectum beginning at the same time as ruminal digesta collection. Fecal samples were dried in a forced-air oven at 55 °C to a constant weight and were ground to pass through a 1-mm screen using a hammer mill (Christie-Norris Laboratory Mill, Christie-Norris Ltd, Chelmsford, UK). All dried and ground feed, refusal, and fecal samples were analyzed for DM, organic matter (OM), crude protein (CP), neutral detergent fiber measured using α-amylase, sodium sulfite, and corrected for ash content (aNDFom), starch, ether extract, calcium, and phosphorus, and the NEm and NEg were calculated at Cumberland Valley Analytical Services (Waynesboro, PA) as described by Pereira et al. (2021). Samples were also analyzed for titanium concentration according to Myers et al. (2004).

Statistical analysis

Heifer was considered as the experimental unit ($n = 8$). The model for all variables included fixed effects of method (dry-rolled vs. tempered), severity (coarse vs. fine), and the method $\times$ severity interaction. Heifer, period, square, and the period $\times$ treatment interactions were included as random effects. All data were analyzed using the PROC MIXED procedure of SAS (SAS Institute, Inc., Cary, NC) with Tukey's

test to compare means. Tests for normality (Shapiro–Wilk and Kolmogorov–Smirnov) and heterogeneity of treatment variances (GROUP option of SAS) were performed before analyzing data. Results were considered significant when the P-value was ≤ 0.05 and trends were considered when $0.05 < P < 0.10$.

Results

Kernel characteristics, starch reactivity, and 7 h in vitro starch digestibility

Interactions were observed ($P \leq 0.01$) between method and severity of processing for all kernel characteristics evaluated (Table 2). For PI (whether reported as a %OM or %DM), tempered grain had greater PI values than when dry-rolled, regardless of severity, and increasing the severity of processing had a greater effect to decrease the PI for dry-rolled than tempered grain. The percentage of fine particles (<1.18 mm) was greater when dry-rolled than when temper-rolled, regardless of the severity of processing, and increasing the severity of processing increased percentage of particles <1.18 mm for dry-rolled hybrid rye only. Kernel width was greater when tempered than dry-rolled and increasing the severity of processing increased kernel width with tempering but not when dry-rolled. The thickness of processed kernels was also greater when tempered than dry-rolled, regardless of processing severity, and increasing the severity of processing decreased thickness to a greater extent for tempering than for dry rolling. Kernel length was greater for tempered than dry-rolled hybrid rye, and increasing the severity of processing reduced the length for dry-rolled but not for tempered hybrid rye.

The AGR (Table 2) was less for tempered vs. dry-rolled hybrid rye but was not affected by the severity of processing. That said, there was a tendency for an interaction between method × severity ($P = 0.06$) where there was a greater increase in AGR for dry-rolled hybrid rye with increased processing than for tempered hybrid rye. While ARIS was not affected by method, severity, or the two-way interaction, tempering hybrid rye increased IRS relative to when dry-rolled, and increasing the severity of processing tended ($P = 0.06$) to decrease IRS. The ISD was increased with tempering and tended to be reduced as the severity of processing increased. As a result, the PRSD was less for tempered than dry-rolled hybrid rye grain but was not affected by severity or the method × severity interaction. The 7 h in vitro starch digestibility was not affected by the method of processing ($P = 0.92$), although increasing the severity of processing increased starch digestibility by 3.9% ($P < 0.01$).

Dry matter intake, particle sorting, and ruminal fermentation

Initial BW and final BW were not affected by method, severity, or the interaction between method and severity ($P \geq 0.06$; Table 3). Heifers fed tempered hybrid rye had greater ($P < 0.01$) DMI when compared to cattle fed dry-rolled hybrid rye, but the processing method had no effect on DMI. There was no effect of the method, severity, or the interac-

tion between method and severity ($P \geq 0.29$) on the sorting index for particles retained on sieves with aperture openings of 19.0 and 8.00 mm. However, heifers fed dry-rolled hybrid rye sorted more against ($P < 0.01$) particles retained on the 4.0 mm sieve than those fed tempered hybrid rye. Cattle fed finely processed hybrid rye increased their sorting against ($P < 0.01$) particles <4.0 mm than those fed coarsely processed hybrid rye.

Mean, minimum, and maximum ruminal pH and the duration that ruminal pH was <5.5 were not affected by method, severity, or the interaction between method and severity ($P \geq 0.12$; Table 3). Cattle fed dry-rolled hybrid rye had a greater ($P = 0.05$) area that ruminal pH was <5.5 when compared to heifers fed tempered hybrid rye with no effect of severity of processing. Total SCFA concentration and the molar proportions of individual SCFA and ruminal ammonia were not affected by method, severity, or the interaction between method and severity ($P \geq 0.23$).

Apparent total tract nutrient digestibility

Heifers fed dry-rolled hybrid rye had greater DM ($P < 0.01$), OM ($P < 0.01$), and CP ($P = 0.01$) digestibility when compared to those fed tempered hybrid rye (Table 4). Increasing the severity of processing did not affect apparent total tract DM, OM, or CP digestibility ($P \geq 0.12$). There was no effect ($P \geq 0.51$) of the method, severity, or the interaction between method and severity on apparent total tract digestibility of aNDFom and ether extract. An interaction was observed ($P = 0.03$) between the method and severity of processing, where increasing the severity of processing for dry-rolled hybrid rye had no effect on starch digestibility but increasing the severity of processing for temper-rolled hybrid rye increased starch digestibility and resulted in values that were not different from those for dry-rolled hybrid rye.

Discussion

The main objective for mechanical processing of small cereal grain kernels such as barley, wheat, and rye for cattle is to damage the pericarp to improve microbial access to the endosperm, thereby enhancing ruminal digestibility (Beauchemin et al. 1993; McAllister et al. 1994). However, excessive processing may increase the proportion of fine particles and the rate and extent of ruminal degradation, thereby increasing risk for nutritional disorders such as ruminal acidosis and bloat (Owens et al. 1997; Mathison 2000). While there are numerous studies evaluating processing methods for barley and corn, there is a paucity of data evaluating how method of processing for hybrid rye grain affects kernel characteristics and starch reactivity. In the current study, we observed that reducing roller gap width had a greater effect to reduce the PI when hybrid rye was dry-rolled than when tempered. The greater reduction in PI was consistent with the greater increase in the proportion of fine particles for dry-rolled hybrid rye than when tempered. While we are not aware of other research evaluating methods of processing for hybrid rye, others evaluating barley (Nixdorff et al. 2020) and corn (Zinn et al. 1998) have also reported a reduction in fine particles when temper-rolled relative to dry-rolled, particu-

Table 2. Effect of method (dry-rolled vs. tempered) and severity (coarse vs. fine) of rolling hybrid fall rye on kernel characteristics, starch reactivity, and 7 h starch digestibility.

Item	Dry-rolled		Tempered		SEM	P		
	Coarse	Fine	Coarse	Fine		Method	Severity	Method × severity
Kernel characteristics								
Process index (% of OM)	80.85[c]	72.70[d]	92.86[a]	88.20[b]	1.21	<0.01	<0.01	<0.01
Process index (% of DM)	80.72[c]	72.40[d]	92.69[a]	87.72[b]	1.37	<0.01	<0.01	<0.01
Particles <1.18 mm (%)	2.13[b]	5.51[a]	0.17[c]	0.21[c]	0.31	<0.01	<0.01	<0.01
Width (mm)	2.35[c]	2.39[c]	3.50[b]	3.87[a]	0.05	<0.01	<0.01	<0.01
Thickness (mm)	1.66[c]	1.54[d]	2.28[a]	1.89[b]	0.02	<0.01	<0.01	<0.01
Length (mm)	6.74[b]	6.22[c]	8.47[a]	8.30[a]	0.06	<0.01	<0.01	<0.01
Starch reactivity								
AGR* (% of starch)	2.65	2.92	2.60	2.64	0.12	<0.01	0.25	0.06
ARIS† (% of starch)	30.57	31.27	31.85	30.08	1.36	0.93	0.75	0.11
IRS‡ (%)	1.92	1.79	2.05	1.89	0.04	<0.01	0.06	0.62
ISD§ (%)	94.40	93.92	94.61	94.37	0.16	<0.01	0.07	0.23
PRSD‖ (%)	91.29	91.21	91.42	91.25	0.07	<0.01	0.17	0.10
7 h starch digestibility (%)	55.13	58.08	55.95	57.35	1.11	0.92	<0.01	0.13

Note: OM, organic matter; DM, dry matter; AGR, amyloglucosidase reactive; ARIS, amylase reactive insoluble starch; ISD, insoluble reactive starch; PRSD, predicted ruminal starch digestion. Superscript letters mean within a row with uncommon superscripts differ ($P < 0.05$).
*Amyloglucosidase reactive soluble starch analyzed according to Zinn (1990) and Rodríguez et al. (2001).
†Amylase reactive insoluble starch analyzed according to Zinn (1990) and Rodríguez et al. (2001).
‡Insoluble reactive starch was calculated as ((ARIS − AGR)/6).
§Insoluble starch digestive, was calculated as $(100 - AGR) \times (IRS/(IRS + 0.06))$, where 0.06 represents the passage rate of grain from the rumen.
‖Predicted ruminal starch digestion was calculated as $(1.32 \times AGR) + (0.93 \times ISD)$ with a maximum value set at 100%.

larly when processed using the same gap width. Increasing severity of processing when tempering generally flattened the kernels making them wider and thinner, while dry rolling reduced the length likely by cracking the kernel, helping to explain the lower production of fines with increasing severity when tempered relative to dry-rolled.

Whereas the processing method and severity interacted to affect kernel characteristics, there were no such interactions on enzymatic measures of starch reactivity or 7 h in vitro starch digestibility. In addition, the processing method tended to alter several measures of starch reactivity. For example, tempering decreased AGR and increased ARIS leading to greater PRSD. By contrast, increasing the severity of processing decreased ARIS. Interestingly, there was little agreement between the PRSD and in vitro 7 h starch digestibility as tempering did not affect digestibility, whereas increasing the severity of processing increased in vitro 7 h digestibility. Greater PRSD for tempered hybrid rye was not expected given the potentially reduced surface area, due to less fine particles, available for enzymatic and microbial degradation and may be an artifact of the methodology required as cereal grains were dried and ground to pass through a 1-mm sieve for this analysis (Zinn 1990; Rodriguez et al. 2001). However, Rajtar et al. (2020) reported that rates of in vitro and in situ digestion of hybrid rye ground to pass through a 4-mm screen were less than those of crushed hybrid rye. These data suggest that finely processing hybrid rye may not necessarily enhance PRSD but increases in vitro starch degradation, while tempering may increase PRSD, but not in vitro degradation challenging the use of these measures as indicators for adequacy of processing and starch availability. Research is needed to develop a methodology that improves the char-

acterization of cereal grain processing without requiring additional processing for the laboratory assay.

The DMI in this study was lower than expected ranging from 1.35% to 1.70% of ending BW. Rusche et al. (2020) also noted lower DMI with increasing dietary inclusion of hybrid rye as a replacement for dry-rolled corn in finishing cattle diets, but only with advancing days on feed. Those authors suggested that part of the intake reduction with dry-rolled hybrid rye may be related to ergot alkaloid exposure. In the present study, the total alkaloid concentration was 1.8 mg/kg, which may help explain the relatively low DMI overall. McLennan et al. (2016) reported a 14% average reduction in DMI for feedlot cattle consuming ergot alkaloids. While ergot alkaloids may have been a contributor to overall low DMI, alkaloids do not provide an explanation for changes in DMI with processing method or severity.

Dry matter intake was nearly 0.9 kg/d less for heifers fed dry-rolled hybrid rye with no effect of processing severity. Despite relatively low DMI, mean ruminal pH was also low averaging 5.76, which may suggest that both the tempered and dry-rolled hybrid rye were rapidly available and degraded in the rumen as reported by Rajtar et al. (2020). Moreover, the area that pH was <5.5 was greater when hybrid rye was dry-rolled relative to hybrid rye that was tempered. It is possible that the increased area that pH was <5.5 provided negative feedback causing a reduction in feed intake (González et al. 2012). Others have reported a reduction in DMI when dry-rolled hybrid rye replaced dry-rolled corn (Rusche et al. 2020), but not when whole hybrid rye was fed (Bauckhaus et al. 2021). It is surprising that increasing the severity of processing of hybrid rye did not affect intake or ruminal fermentation as increasing the severity of processing of barley grain,

Table 3. Effect of method (dry-rolled or tempered) and severity (coarse or fine) of rolling for hybrid fall rye on body weight (BW), dry matter intake (DMI), ruminal fermentation, and particle sorting of ruminally cannulated beef heifers ($n = 8$).

Item	Dry-rolled		Tempered		SEM	P		
	Coarse	Fine	Coarse	Fine		Method	Severity	Method × severity
Initial BW (kg)	329.1	331.6	322.0	327.9	15.22	0.06	0.13	0.52
Final BW (kg)	342.7	342.2	342.5	342.4	18.51	0.82	0.93	0.76
DMI (kg)	4.92	4.62	5.82	5.45	0.56	0.01	0.15	0.77
DMI variation (%)	7.65	7.72	8.00	5.94	1.35	0.31	0.96	0.13
Particle sorting index*								
>19.0 mm	108.02	108.21	106.83	102.99	3.61	0.29	0.55	0.51
<19.0 to >8.0 mm	108.03	107.92	105.15	105.85	3.00	0.39	0.92	0.89
<8.0 to >4.0 mm	91.22	96.63	101.45	102.32	2.4	<0.01	0.20	0.35
<4.0 mm	100.56	95.65	98.24	95.09	1.82	0.30	<0.01	0.52
Ruminal pH								
Mean pH	5.8	5.63	5.82	5.77	0.20	0.48	0.39	0.33
Minimum pH	5.12	4.94	5.29	5.21	0.18	0.27	0.31	0.32
Maximum pH	6.48	6.48	6.34	6.38	0.24	0.23	0.90	0.65
Duration that pH <5.5 (min/d)	481.34	639.91	342.97	491.72	231.67	0.29	0.12	0.96
Area that pH <5.5 ((pH × min)/d)	161.91	368.83	100.28	174.14	111.28	0.04	0.15	0.19
Ruminal fermentation								
Total SCFA[†] (mmol/L)	84.49	83.73	89.57	87.95	5.36	0.12	0.68	0.88
SCFA proportions (mol/100 mol[4])								
Acetate	42.12	41.25	39.94	41.42	1.5	0.30	0.75	0.23
Propionate	33.53	34.27	33.58	34.63	1.42	0.88	0.41	0.89
Butyrate	18.54	18.64	20.51	18.26	1.23	0.47	0.33	0.29
Valerate	2.86	2.95	2.54	2.59	0.62	0.47	0.89	0.97
Isovalerate	2.05	1.95	2.34	2.11	0.25	0.21	0.33	0.71
Isobutyrate	0.84	0.9	0.94	0.95	0.06	0.23	0.60	0.65
NH$_3$-N[‡] (mg/dL)	11.16	9.99	11.74	11.45	1.09	0.24	0.40	0.61

Note: BW, body weight; DMI, dry matter intake; SCFA, short-chain fatty acids.
*Particle sorting index was calculated as ((actual intake)/(theoretical intake)) × 100 (as fed basis), as described by Leonardi and Armentano (2003).
[†]Short-chain fatty acids, $n = 32$ for total SCFA.
[‡]NH$_3$-N ($n = 32$).

Table 4. Effect of method (dry-rolled or tempered) and severity (coarse or fine) of hybrid fall rye on apparent total tract nutrient digestibility of ruminally cannulated beef heifers ($n = 8$).

Item	Dry-rolled		Tempered		SEM	P		
	Coarse	Fine	Coarse	Fine		Method	Severity	Method × severity
DM (%)	79.23	80.48	77.06	78.95	0.72	<0.01	0.12	0.58
Organic matter (%) DM	77.60	79.74	68.19	72.95	2.71	<0.01	0.23	0.49
Crude protein (%) DM	75.47	76.22	72.82	74.43	1.43	<0.01	0.38	0.54
aNDFom (%) DM	58.06	58.47	58.39	57.81	1.66	0.92	0.96	0.77
Starch (%) DM	97.97[a]	98.08[a]	92.76[b]	95.86[a]	0.87	<0.01	0.10	0.03
Ether extract (% DM)	70.75	68.27	68.12	66.65	4.62	0.67	0.63	0.99

Note: DM, dry matter; aNDFom, neutral detergent fiber measured using alpha amylase and sodium sulfite corrected for ash content. Superscript letters mean within a row with uncommon superscripts differ ($P < 0.05$).

to values similar to those in the current study, decrease DMI (Wang et al. 2003; Moya et al. 2015; Ribeiro et al. 2016). These data collectively suggest that part of the intake reduction may be related to greater ruminal starch availability for dry-rolled than tempered hybrid rye grain.

Minimum, mean, and maximum pH values were not affected by the method of processing, but the area that pH was <5.5 was greater for dry-rolled than tempered hybrid rye. While the roller gap width was the same for the two processing methods, dry rolling increased the production of fines relative to tempered hybrid rye and shortened kernel length. These data suggest that ruminal starch degradation was greater for dry-rolled hybrid rye leading to increased area that pH was <5.5. The concept that dry-rolled hybrid rye was more available than tempered hybrid rye is supported by the finding that dry-rolled rye had greater area that pH was <5.5 and greater PRSD. The greater area that pH was <5.5 is consistent with in situ findings of Wang et al. (2003) where tem-

pering barley prolonged the lag time, thereby reducing effective degradability and ruminal in situ DM disappearance. Hironaka et al. (1979) also reported lower ruminal pH in cattle fed diets containing more finely ground barley when compared to cattle fed coarser diets.

Although the area that pH was <5.5 was affected by the processing method, the total concentration of SCFA and the molar proportions of individual SCFA were not affected by treatments. Given minimum pH values averaging 5.03 and 5.25 for dry-rolled and temper rolled hybrid rye, respectively, and the modest total concentration of SCFA (86.5 mmol/L), it is possible that other acids such as lactic acid may have contributed to the pH decline. We are not aware of other studies evaluating ruminal fermentation of hybrid rye and suggest that future research should include the measurement of lactic acid in ruminal fluid.

In the present study, tempering hybrid rye decreased apparent total tract digestibility of DM, OM, and CP, further supporting that dry rolling increased effective surface area for digestion relative to tempered hybrid rye. We are not aware of other research evaluating apparent total tract digestibility for hybrid rye varieties, but using barley grain, Wang et al. (2003) reported a 45% reduction in the rate of ruminal DM degradation for tempered relative to dry-rolled barley. In addition, total tract starch digestibility was increased for tempered barley with increased severity of processing, but not for dry-rolled. Importantly, finely tempered hybrid rye had total tract starch digestibility that was not different from dry-rolled hybrid rye. While we cannot confirm the site of digestion in the present study, past research has reported that rye starch is highly available in the rumen (Krieg et al. 2017; Rajtar et al. 2020), further confirming the suggestion that tempering at the same roller gap width as the dry-rolled treatments may have limited ruminal starch availability.

Conclusion

In conclusion, the processing method of hybrid fall rye affects DMI, ruminal pH, and apparent total tract nutrient digestibility in ruminally cannulated beef heifers. Generally, tempering may allow for a greater severity of processing without marked reductions in DMI and ruminal pH, while achieving suitable total tract starch digestibility. For dry-rolled hybrid rye, increasing the severity of processing (81% vs. 73% PI) had no effect on DMI or ruminal pH, despite increasing production of fine particles and increasing 7 h in situ digestibility. More research designed to evaluate the optimal processing severity for hybrid rye as affected by the processing method and to improve characterization of ruminal fermentation is needed to better understand feeding management strategies for hybrid rye as a cereal grain for finishing cattle.

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Data availability
Data are held at the University of Saskatchewan. Queries to access the data should be made through the corresponding author.

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Competing interests
Outside of project funding, MCS Pereira, JA Johnson, and GB Penner declare no conflict of interest. RS Brittain and H Wehrle are employed by KWS Cereals USA, LLC, and KWS Seeds Canada, Ltd., respectively.

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