Evaluating the effect of finely ground, dry-rolled, and crumbled corn grain on performance, feeding behavior, and starch digestion in Holstein dairy heifers

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ABSTRACT

Corn processing methods including finely ground (FGC), dry rolled (DRC), and crumbled corn (CRC) were evaluated to determine their effects on average daily gain (ADG), structural growth, starch digestibility, feeding behavior, and blood metabolites of young dairy heifers. In this study, 36 Holstein heifers [91 ± 4 d of age, 105 ± 6.5 kg of body weight (BW); mean $\pm$ standard deviation] housed in 9 pens (4 heifers per pen) were fed diets (dry matter basis) containing 20% forage (wheat straw) and 80% corn-based concentrate for 60 d. Pens were randomly assigned to 1 of 3 dietary treatments based on the type of corn grain used for the diets: (1) ground corn (FGC; fine: 1.11 ± 0.52 mm); (2) dry-rolled corn (DRC; 2.30 ± 0.68 mm); and (3) crumbled corn (CRC; 2.54 ± 0.70 mm). Heifers had ad libitum access to diets and water throughout the experiment and the feed intake was measured daily. Animals were weighed at the beginning (91 d of age) and end (151 d of age) of the study. The ADG (kg of BW/d) was calculated at the end of experiment at an individual level. Feeding behavior was recorded based on direct observation by monitoring each heifer every 5 min during a 22-h period at 150 d of age. The CRC and DRC tended to increase feed intake compared with FGC, whereas heifers fed CRC tended to have a greater withers height compared with other treatments. Feed efficiency was not affected; however, ADG and final

BW increased in heifers fed the CRC diet compared with other diets. Feeding CRC increased total-tract starch digestibility compared with FGC and DRC diets (97.8 vs. 93.1 and 89.5%, respectively). Compared with FGC diet, feeding DRC and CRC tended to increase rumination time. The molar proportion of propionate was greater, and the molar proportion of acetate and acetate-to-propionate ratio were lower in heifers fed CRC than in those fed DRC. The blood glucose and insulin-like growth factor concentrations increased in heifers fed CRC compared with feeding DRC; however, blood urea concentrations decreased by CRC feeding. In conclusion, thermal processing (CRC diet) improved total-tract starch digestibility, ADG, feed intake, and skeletal growth, but had no effect on feed efficiency during the experimental period. Our results indicated that the thermal processing of corn grain improved growth performance of weaned heifers; however, the performance of heifers over a 60-d period did not differ between mechanical processing methods (grinding and dry rolling).

Key words: crumbling, feeding behavior, growth, heifer

INTRODUCTION

Feeding management of dairy heifers is labor intensive and expensive, often accounting for ~15 to 20% of the total farm expenses (Heinrichs, 1993; Hoffman, 1997). Hence, optimizing feeding strategies for raising dairy heifers are essential to minimize rearing costs and increase the profitability of dairy operations (Wang et al., 2017). Corn grain is the predominant source of dietary starch and relatively high levels of corn grain is usually used primarily for calf and heifer diets.

Maximizing corn digestibility, particularly when feeding expensive diets, is a key issue in dairy heifer

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diets. Therefore, mechanical (grinding and rolling) and thermal (steam-flaking and pelleting) processing enhances starch digestibility of corn grain by both microorganisms and pancreatic enzyme action (Offner et al., 2003; Hoffman et al., 2012). Grinding is the most common corn processing method used for dairy cattle feeding; however, it may not have an effect on animal performance. Owens et al. (1997) reviewed studies on beef cattle and reported that cattle fed whole-shelled corn had similar ADG but lower DMI than those fed dry-rolled corn. Porter et al. (2007) observed higher ADG and starter intake, and earlier initiation of rumination in calves fed a coarse meal diet as opposed to a finely ground diet. Earlier studies with limited details about methods and diets (Lassiter et al., 1955; Gardner, 1967) reported that starter intake and ADG were lower when starters were fine meals compared with coarse particle grains as in mashed or textured diets. However, the ingredients and nutrient composition of their diets were dissimilar, thereby confounding the interpretation of results. Starch availability and digestibility is typically higher in finely ground and dry-rolled grains compared with whole grains (Theurer, 1986; Huntington, 1997; Crocker et al., 1998). In addition, compared with coarsely ground corn, the digestion of finely ground corn is faster in the rumen and more complete across the total digestive tract in dairy cattle (Rémond et al., 2004).

Pelleting corn grain (a mechanical processing with high temperature) has been considered the second most common method of corn processing. Pelleting not only improves palatability but was also reported to reduce ingredient segregation and wastage of starter feeds (Abdollahi et al., 2018). Some manufacturers implement a crumbling process after pelleting, which is a type of feed prepared at the mill by pelleting of the mixed ingredients and then crushing the pellet into a coarser particle size than mash (Abdollahi et al., 2018). This form of feed is more popular in broiler and swine diets due to its ease of feeding. Choi et al. (1986) reported that chickens fed the crumbled starter diet had greater intake and Reece et al. (1984) observed that pigs fed a high-energy crumble and high-protein profile had the best feed conversion efficiency. Also, Nguyen et al. (2017) reported a greater ADG and feed efficiency (FE) in pigs fed a crumble diet rather than mash diet for identical feed intake. However, no research has investigated the effect of crumbled corn on BW gain and metabolic response in dairy heifers.

We are not lacking literature on the physical characteristics and processing of dairy heifer starter diets; however, industry could benefit from a more systemic approach to identify specific forms or processing methods of corn that are best for heifer performance. We

hypothesized that dry-rolled and crumbled corn can increase feed intake and starch digestibility, with a direct bearing on growth performance and blood metabolites in heifers. The objective of this study was to evaluate the effect of crumbled, dry-rolled, and finely ground corn on intake, growth performance, feeding behavior, and blood metabolites of young heifers fed corn-based starter diets.

MATERIALS AND METHODS

Research Facilities and Animals

The present study was carried out at a commercial dairy farm (Astan Ghods Razavi Dairy Farm, Tabbas) at South Khorasan Province, Iran. All experimental procedures and animal manipulations were approved according to the guidelines of the Iranian Council of Animal Care (1995). Thirty-six Holstein heifers were used in this study. Before the start of the study, all calves were housed in individual pens bedded with wheat straw in a curtain-sided, naturally ventilated nursery. They were fed 4 L/d of pasteurized whole milk ($3.52 \pm 0.09\%$ fat, $3.15 \pm 0.05\%$ CP, $4.80 \pm 0.04\%$ lactose, and $11.5 \pm 0.09\%$ TS) in buckets twice daily at 0800 and 1700 h before weaning. Calves were fed (ad libitum) a 40% starch and 20% CP mashed starter made with ground corn, soybean meal (44% CP), canola meal, wheat bran, salt, and vitamin and mineral mix during pre- and postweaning periods. Calves were weaned at 70 d of age and kept for 10 d in respective individual pens. At 81 d of age, young heifers were housed according to initial BW in a naturally ventilated fence sidewall, straw-bedded barn in 9 pens of 4 heifers/pen ($3.98 \text{ m}^2/\text{head}$) for 70 d (10 and 60 d for adaptation and experimental period, respectively; 3 pens/treatment). On the first day of study, all heifers in the pens averaged 91 ± 4 d and 105 ± 6.50 kg of BW (mean $\pm$ SD). Diets were offered to each pen daily at 0800 and 1600 h, and refusals were collected and weighted every morning for intake estimation. Daily feed amounts for pen fed twice per day were divided into 2 equal amounts with the second half of feed kept in an air-conditioned room (12°C) in the barn until the second delivery. The total amount of feed offered to each pen was adjusted weekly to keep 5% refusal (on an as-fed basis). Animals had access to a water trough ($0.15 \times 0.8 \times 0.25$ m width, length, and height, respectively) and TMR from a feed bunk ($0.52 \times 1.5 \times 0.15$ m width, length, and height, respectively) during the experimental period that was accessible from the feed alley. Experimental duration was 60 d and the study finished when heifers were 151 d of age. Animals were under the regular supervision of a veterinarian.

Table 1. Ingredients and chemical composition of the experimental starter feeds

Item	Treatment ¹		
	FGC	DRC	CRC
Ingredient, % of DM			
Wheat straw	20.0	20.0	20.0
Ground corn	50.0	—	—
Crumbled corn	—	—	50.0
Dry-rolled corn	—	50.0	—
Soybean meal, 45% CP	20.5	20.5	20.5
Canola meal	4.50	4.50	4.50
Sugar beet pulp	3.00	3.00	3.00
Vitamin and mineral mix ²	1.00	1.00	1.00
Calcium carbonate	0.50	0.50	0.50
Salt	0.50	0.50	0.50
Nutrient composition, % of DM (unless otherwise noted)			
ME, ³ Mcal/kg	2.78	2.79	2.78
NE _G , ³ Mcal/kg	1.78	1.78	1.77
DM	88.7	89.3	89.0
Starch	38.2	38.4	38.3
NDF ⁴	24.0	24.2	24.2
ADF	14.6	14.7	14.6
CP	17.1	17.0	17.1
Ether extract	3.81	3.71	3.93
NFC ⁵	56.7	56.3	56.9

¹Treatment = FGC: finely ground corn; DRC: dry-rolled corn; CRC: crumbled corn.

²Contained per kilogram of supplement: 975,000 IU of vitamin A, 750,000 IU of vitamin D, 1,800 IU of vitamin E, 143 g of Zn, 76 g of Mn, 48.6 g of Cu, 19.5 g of Se, 18.4 g of Fe, 8 g of Ca, and 1.3 g of Co.

³Calculated from NRC (2001).

⁴aNDF (NDF assayed with a heat-stable amylase) without sodium sulfate.

⁵Nonfiber carbohydrate was calculated as 100 – (CP + NDF + ether extract + ash; NRC, 2001).

Experimental Design, Treatments, and Corn Processing

Heifers were fed common TMR diets during the adaptation period with a forage-to-concentrate ratio of 20:80. Diets were formulated to achieve an ADG of 0.9 kg/d (NRC, 2001; Table 1). Dietary ingredients were mixed in a TMR mixer wagon (model 911517, Isfahan Dor Motaghayer Co.), and the appropriate amount of TMR was manually weighed out for each pen. Treatments differed in the types of corn processed for the TMR: (1) finely ground corn (**FGC**), (2) dry-rolled corn (**DRC**), and (3) crumbled corn (**CRC**). Treatments were randomly allotted to experimental pens, resulting in 3 pens per treatment.

Corn grain was ground by a hammer mill (model SPEC 132X36C/A, Yangzhou) equipped with a 2.0 mm for FGC. Dry-rolled corn was processed to a mean particle size of 2.3 mm through a roller mill (45 to 73 cm rollers). Pelleting process was performed by introducing ground corn to the conditioner and injecting steam along with 80°C temperature and 1-min retention time and was pelleted through a 4-mm die using a pellet mill (model MUZL 610, Yangzhou). The pelleted corn was finally crumbled to 2- to 3-mm pieces and crumbles were cooled to a temperature of ~22°C. Particle size of

the processed corn grains was measured by dry sieving in duplicate using an automatic vibratory sieve shaker (model 120, Techno Khak, Khavaran) with 4.75-, 2.36-, 1.18-, 0.6-, 0.3-, and 0.15-mm diameter screens (Table 2). Briefly, 100 g of processed corn grain was placed on the top screen and the stack of sieves was shaken until the distribution of materials did not change (~10 min). Geometric mean particle size in the ground, dry-rolled, and crumbled corn (1.11, 2.30, and 2.54 mm, respec-

Table 2. Characterization of corn particle size among corn processing methods

Item	Corn grain		
	Ground	Dry-rolled	Crumbled
Retention on the sieve, g/kg			
4.75 mm	0.40	0.31	0.36
2.36 mm	12.0	85.0	90.1
1.18 mm	37.3	5.9	5.85
0.6 mm	34.6	4.45	2.75
0.3 mm	15.2	2.22	0.52
0.15 mm	0.40	1.01	0.10
Pan	0.10	1.11	0.32
Geometric mean size, ¹ mm	1.11	2.30	2.54

¹Geometric mean particle size; calculated as described by the American Society of Agricultural Engineers (ASAE, 1983).

tively) was calculated as described by the American Society of Agricultural Engineers (ASAE, 1983).

Experimental Measurements and Sampling

Pen feed intake was measured every morning (0800 h) based on offered and refused quantities of feed. Heifers were weighed before morning feeding at the start (d 91 of age) and end (d 151 of age) of the study using an electronic scale (model EES-500; Ettehad Inc.), which was placed in the small pen close to animal pens. Average daily gain (kg of BW/d) was calculated at the end of the experiment at an individual level. Feed efficiency was computed as ADG per kilogram of DMI. Body condition score (up to 1-unit difference using a 5-point scale, where 1 = thin and 5 = fat; Wildman et al., 1982) was measured on the initial and final day of the study.

Five fecal grab samples per heifer were taken at 0600, 1000, 1400, 1800, and 2200 h during the last 7 d of the experiment. Fecal samples collected at different time points were composited daily (equal amount on a fresh weight basis) into one sample per heifer, combined on an equal wet weight basis, and subsampled for analyses. Acid insoluble ash (Van Keulen and Young, 1977) was used as an internal marker in feeds and fecal samples to estimate nutrient digestibility. Feeds and feces were analyzed for DM, ash, CP, NDF, and starch concentrations.

For chemical analyses, feed samples were oven-dried at 60°C for 72 h, ground to pass through a 1-mm screen (Wiley mill standard model 4; Arthur H. Thomas Co.), and subsequently analyzed for CP (AOAC, 1990; method 988.05), aNDF (NDF assayed with a heat-stable amylase and expressed inclusive of residual ash) without the use of sodium sulfite (Van Soest et al., 1991), ADF (AOAC, 1990; method 973.18), and ash (AOAC, 1990; method 942.05). Ether extract concentration was determined using a Soxhlet Gerhardt apparatus (model SE 416, Gerhardt). Nonfiber carbohydrate component was calculated as $100 - (\text{CP} + \text{NDF} + \text{ether extract} + \text{ash})$ (NRC, 2001). Total starch content in feed and feces was determined using Megazyme Total Starch Assay Kit (Megazyme International Ireland Ltd.) following the approved method (76–13.01; AACCI International, 1999).

Body measurements including hip width (distance between the points of hook bones), withers height (distance from the base of the front feet to the withers), and body length (distance between the points of shoulder and rump) were taken at the beginning (d 91) and the end (d 151 of experimental period) of the trial according to the method described by Khan et al. (2007). Behavioral activity was used as an indica-

tion of animal welfare and comfort. Behavioral data including eating (head in trough accompanied by ingesting TMR), standing (standing with all 4 feet on the ground or standing with just 2 hooves without any purposeful activity), ruminating (irregular, repetitive chewing without discernible food in the mouth either lying or standing), and lying (lying on flank or sternum with head held in a raised position or down, without rumination) were monitored for 22 h (between 0800 and 0600 h) on d 150 as described previously by von Keyserlingk et al. (2011) and Abdelfattah et al. (2013). Behavioral activities of the heifers were recorded by 3 trained observers from a distance of 2 to 3 m, and every effort was made not to disturb the heifers in any way. All activities were noted every 5 min and each activity was assumed to persist for the entire 5-min interval between observations. A period of eating was defined as at least 1 observation of eating activity occurring after at least 5 min without eating. Intervals between feeding events were calculated from the end of a feeding event to the beginning of the next and averaged for each heifer. The same procedure was used to compute the rumination pattern. A period of lying was defined as at least 1 observation occurring after at least 5 min without lying activity.

Ruminal fluid samples were obtained using a stomach tube 4 h after the morning feeding on d 151 of the study. Ruminal contents were squeezed through 4 layers of cheesecloth. To avoid saliva contamination, the first 50 mL of ruminal fluid was discarded. Ruminal fluid pH was recorded using a pH meter (Metrohm 744). For VFA determination, 10 mL of ruminal fluid was acidified with 3 mL of 25% metaphosphoric acid and stored at –20°C until analysis. Ruminal samples were analyzed for VFA using gas chromatography (model CP-9002, Chrompack) equipped with a 50-m (0.32 mm i.d.) silica-fused column (CP-Wax Chrompack Capillary Column, Varian). Helium and crotonic acid (*trans*-2-butenic acid) were used as the carrier gas and the internal standard, respectively. The initial and final oven temperatures were 55 and 195°C, respectively, and detector and injector temperatures were set at 250°C.

Blood samples were obtained on d 151 of the study by venipuncture of the jugular vein into an evacuated tube containing K₂EDTA (Becton Dickinson Vacutainer Systems) 4 h after the morning feeding and immediately placed on ice. Tubes were centrifuged at $3,000 \times g$ for 20 min at room temperature to separate the plasma, which was then stored at –20°C for subsequent analysis. Plasma glucose (catalog numbers: 1–500–017), urea N (catalog numbers: 1–400–029), total protein (catalog numbers: 9304), and albumin concentrations were analyzed using commercial kits (Pars Azmoon Kit; Pars Azmoon) by an automated analyzer

(Technicon-RA 1000 Auto analyzer; DRG Instruments GmbH). Insulin concentration was measured with an RIA kit (PI-12K, Millipore Oy). Intra- and interassay coefficients of variation for insulin were 5.4 and 6.3%, respectively. Concentration of IGF-1 was determined by an automated biochemistry analyzer (model GF-D200, Caihong Co.). Plasma concentration of nonesterified fatty acids (colorimetric method, kit no. FA 115) and BHB (enzymatic method, based on 3-hydroxybutyrate dehydrogenase, kit no. RB1007) were also measured using commercial kits (Randox Laboratories Ltd.) and a spectrophotometer (UNICCO, 2100, Zistchemi Co.). The liver function indicator enzymes, aspartate aminotransferase (**AST**) and alanine aminotransferase (**ALT**), were measured using ELISA (Roche Hitachi 717 Chemistry Analyzer, GMI Co.) and commercial laboratory kits (kit no. 92005 and 92004 for AST and ALT, respectively).

Statistical Analysis

Before analyses, all data were screened for normality using the UNIVARIATE procedure of SAS. The effect of treatments on DMI was tested by obtaining the mean value of the pen (based on the mean of the 4 heifers per pen in the treatment) on each experimental day. Feed intake, ADG, and FE data were analyzed using the MIXED procedure of SAS (SAS 9.4, SAS Institute Inc.) as completely randomized design with repeated measures. The model consisted of treatment (grain processing), time (day), and respective interactions as fixed effects, and pens as a random effect using pen-based statistical models described by St-Pierre (2007). Time (day) was a repeated measure using an autoregressive type 1 covariance structure assisted by the lowest Bayesian information criterion (fit statistic) level.

Data for BW, skeletal growth, digestibility, behavior (min/22 h), rumen fermentation, and blood metabolites were obtained from each individual heifer and analyzed without the effect of day. The model consisted of treatment as fixed effect, and pen nested within treatment as random effect. Significance among treatments was tested using ANOVA. The threshold of significance was set at $P \leq 0.05$; trends were declared at $0.05 < P \leq 0.10$.

RESULTS

Diets were formulated for 17% CP and 38% starch (DM basis; Table 1) and all experimental diets had similar nutrient composition. The characterization of corn particle size showed greater proportion of particles

<2 mm in diameter for ground compared with dry-rolled and crumbled corn (Table 2).

There was no difference between treatments for FE, initial hip height, and initial withers height of heifers in experimental pens (Table 3). Final BW ($P = 0.04$), ADG ($P = 0.01$), hip height change ($P < 0.01$), and withers height change ($P = 0.03$) were greater ($P < 0.05$) in heifers fed CRC compared with feeding FGC and DRC diets. Dry matter intake tended to increase with DRC and CRC compared with FGC diets ($P = 0.08$). The final hip height ($P = 0.07$) and the final withers height ($P = 0.09$) tended to be greater in heifers fed CRC compared with FGC or DRC diets; however, no treatment differences were observed for initial ($P = 0.82$) and final BCS ($P = 0.31$), and BCS change ($P = 0.28$). Dry matter, NDF, and CP digestibilities were not affected by diets; however, feeding CRC diet increased ($P = 0.04$; Table 4) OM digestibility compared with other diets. Crumbled corn diets increased total-tract starch digestibility by 9% in comparison to the average values of FGC and DRC diets (Table 4). Corn processing did not affect the time spent standing, lying, and eating, but rumination time tended to be lower in FGC heifers than in DRC and CRC heifers (Table 4).

Feeding processed corns had no effect on ruminal pH, total VFA, and molar proportion of butyrate, valerate, isobutyrate, and isovalerate (Table 5). However, the molar proportion of ruminal propionate was greater ($P < 0.01$), molar proportion of acetate was lower ($P = 0.04$), and acetate-to-propionate ratio was higher in heifers fed DRC compared with feeding CRC diets ($P = 0.02$; Table 5).

Corn processing did not alter the plasma concentrations of insulin, total protein, albumin, AST, ALT, BHB, and nonesterified fatty acids (Table 6). However, the plasma concentration of IGF-I spiked ($P = 0.02$) and glucose tended to increase ($P = 0.08$) in heifers fed CRC compared with those fed DRC, but CRC and FGC diets did not differ. Furthermore, feeding CRC decreased ($P = 0.04$) plasma urea N concentration compared with the DRC diet.

DISCUSSION

Commercial starter feeds are pelleted, mashed, or textured, with the latter consisting of a mixture of coarsely rolled or ground grains, whole grains, and some pellets. A host of studies (e.g., Bach et al., 2007; Porter et al., 2007; Hill et al., 2008) have evaluated the effects of the physical form (e.g., mashed, pelleted, and textured) of the starter feed on intake and growth performance, but the results of these studies are inconsistent concerning young calves. Franklin et al. (2003) concluded that

Table 3. Effects of corn grain processing on feed intake, BW, ADG, skeletal growth, and BCS of heifers¹

Item	Treatment ²				P-value		
	FGC	DRC	CRC	SEM	Treatment	Week	Treatment × week
Initial BW, kg	103.2	103.6	103.9	0.93	0.96	—	—
Final BW, kg	159.3 ^b	158.0 ^b	164.2 ^a	1.11	0.04	—	—
ADG, kg	1.00 ^b	0.97 ^b	1.10 ^a	0.04	0.01	0.30	0.06
Total DMI, kg/d	4.03	4.28	4.35	0.07	0.08	<0.01	0.90
Feed efficiency ³	0.24	0.23	0.25	0.01	0.66	<0.01	0.26
Initial hip height, cm	100.6	101.5	103.1	1.13	0.87	—	—
Final hip height, cm	110	108	115	1.43	0.07	—	—
Hip height change, cm	10.1 ^b	9.85 ^b	13.7 ^a	0.74	<0.01	—	—
Initial withers height, cm	96.8	95.7	97.0	1.20	0.71	—	—
Final withers height, cm	106	104	111	2.23	0.09	—	—
Withers height change, cm	9.60 ^b	10.1 ^b	14.5 ^a	0.70	0.03	—	—
Initial BCS ⁴	2.40	2.43	2.46	0.06	0.82	—	—
Final BCS	2.86	2.93	2.98	0.05	0.31	—	—
BCS change	0.46	0.50	0.53	0.02	0.28	—	—

^{a,b}Means with different superscripts within a row indicate a *P*-value ≤ 0.05.

¹n = 3 experimental pens per treatment; 4 heifers/pen.

²Treatment = FGC: finely ground corn; DRC: dry-rolled corn; CRC: crumbled corn.

³Feed efficiency = ADG/total DMI.

⁴1 to 5 system based on Wildman et al. (1982).

a texturized starter improved performance compared with a ground starter. There is scant evidence in the literature that suggests coarse or texturized starters should perform better than finely ground starters. In the current study, DMI tended to be greater in heifers receiving texturized diets (CRC and DRC), which agrees with previously reported intake trends (Bate-man et al., 2009), where calves fed corn-based starter with a high content of fine particles had a lower starter intake compared with feeding textured starter. Lower DMI was previously reported for calves fed starter feed with fine particles compared with calves fed starter feed with large particles (Gardner, 1967). Corn processing in the current experiment changed the physical char-

acteristics of the corn grain in experimental diets as evident from lower particle size for FGC (1.11 mm), compared with particle size for DRC (2.30 mm) and CRC (2.54 mm). Yu et al. (1998) reported lower DMI for cows fed diets with finely ground dried corn relative to diets containing other types of corn (coarsely ground, steam-flaked, and steam-rolled). Based on the hepatic oxidation theory (Allen et al., 2009), propionate entering the liver may induce satiety signals to which the animals respond by lowering feed intake. We can speculate that greater propionate concentration with FGC may have lowered feed intake in this study; however, this explanation may not be entirely applicable in this study because ruminal propionate from FGC-fed

Table 4. Effects of corn grain processing on digestibility, fecal starch, and feeding behavior in heifers¹

Item	Treatment ²			SEM	P-value
	FGC	DRC	CRC		
Nutrient digestibility, % DM basis					
DM	76.3	75.4	75.3	0.86	0.64
OM	75.5 ^b	74.7 ^b	78.6 ^a	0.49	0.04
NDF	47.7	48.2	48.7	0.48	0.69
CP	71.0	71.9	70.6	1.04	0.66
Starch	93.1 ^b	89.5 ^c	97.8 ^a	0.64	0.01
Fecal starch	3.8 ^{ab}	5.4 ^a	2.1 ^b	1.34	0.03
Feeding behavior					
Standing, min/22 h	246	267	255	10.1	0.52
Lying, min/22 h	434	405	416	17.5	0.79
Eating, min/22 h	291	278	284	8.58	0.71
Rumination, min/22 h	315	345	340	8.18	0.06

^{a,b}Means with different superscripts within a row indicate a *P*-value ≤ 0.05.

¹n = 3 experimental pens per treatment; 4 heifers/pen.

²Treatment = FGC: finely ground corn; DRC: dry-rolled corn; CRC: crumbled corn.

Table 5. Effects of corn grain processing on ruminal fermentation parameters in heifers¹

Item	Treatment ²			SEM	P-value
	FGC	DRC	CRC		
Ruminal pH	5.89	6.02	5.86	0.18	0.16
Total VFA, mM	104	103	108	3.30	0.34
Individual VFA, mol/100 mol					
Acetate	44.8 ^{ab}	48.2 ^a	42.8 ^b	1.52	0.04
Propionate	38.1 ^{ab}	35.3 ^b	40.4 ^a	0.28	<0.01
Butyrate	12.0	11.5	11.8	1.76	0.61
Valerate	4.02	4.10	3.82	0.42	0.36
Isobutyrate	0.33	0.31	0.35	0.08	0.91
Isovalerate	0.54	0.52	0.63	0.11	0.45
Acetate:propionate ratio	1.18 ^{ab}	1.36 ^a	1.05 ^b	0.08	0.02

^{a,b}Means with different superscripts within a row indicate a *P*-value ≤ 0.05.

¹*n* = 3 experimental pens per treatment; 4 heifers/pen.

²Treatment = FGC: finely ground corn; DRC: dry-rolled corn; CRC: crumbled corn.

heifers was not different than DRC or CRC. Along with ruminal propionate, low ruminal pH may influence feed intake as smaller particle size may favor the microbial and enzymatic access to starch, thereby increasing the rate of ruminal starch degradation, causing a faster decline in pH (Owens et al., 1998). In the present study, ruminal pH was above the benchmark for SARA (pH >5.6); however, ruminal pH <6 is associated with irregular patterns of feed consumption and may result in lower feed intake (Krause et al., 2002). Gelsinger et al. (2020) reported that low ruminal pH and severity of SARA negatively affect feed intake and growth performance of dairy calves from 4 to 16 wk of age. Although we did not find treatment effects on ruminal pH, the pH measurements were based on spot samples and may not be representative since continuous measurement of ruminal pH provides a better indication of ruminal pH fluctuations. Second, although low ruminal pH and severity of SARA appeared to negatively af-

fect feed intake and performance in cattle (Moya et al., 2015; Malekkhahi et al., 2016), long-term effects of low ruminal pH with a greater proportion of concentrates on growth performance and feed intake of young heifers warrant further investigation.

Mechanical (grinding, rolling, and so on) and thermal processing (conditioned pellet) of the corn starch fosters the ability of microbes and enzymes to hydrolyze the starch granule. In this study, heifers fed CRC had greater daily gain and final BW compared with feeding FGC and DRC diets. Similarly, Newland et al. (1962) reported numerical increase in final BW and greater ADG in steers fed crumbled corn diets compared with feeding diets containing ground or shelled corn. Recently, Makizadeh et al. (2020) observed greater ADG in calves fed heat-processed corn (steam-flaked vs. ground corn) during the postweaning period. Further, in terms of amount and type of carbohydrates provided in the starter feed, a recent meta-analysis (Hu et al., 2018)

Table 6. Effects of corn grain processing on blood metabolites in heifers¹

Item	Treatment ²			SEM	P-value
	FGC	DRC	CRC		
Glucose, mg/dL	92.7	87.5	94.1	1.36	0.08
Insulin, µIU/mL	8.20	8.75	9.15	0.53	0.15
IGF-I, ng/mL	179 ^{ab}	168 ^b	184 ^a	5.10	0.02
Urea N, mg/dL	14.7 ^{ab}	15.6 ^a	13.2 ^b	0.86	0.04
Total protein, g/dL	7.17	7.32	6.98	0.18	0.40
Albumin, g/dL	3.75	3.60	3.72	0.17	0.79
Aspartate aminotransferase, IU/L	60.7	61.8	66.8	4.55	0.38
Alanine aminotransferase, IU/L	28.5	26.3	25.1	2.01	0.49
BHB, mg/dL	16.0	13.8	14.5	1.50	0.36
NEFA, ³ mg/dL	93	96	100	4.67	0.77

^{a,b}Means with different superscripts within a row indicate a *P*-value ≤ 0.05.

¹*n* = 3 experimental pens per treatment; 4 heifers/pen.

²Treatment = FGC: finely ground corn; DRC: dry-rolled corn; CRC: crumbled corn.

³NEFA = nonesterified fatty acids.

reported that performance in young calves is positively correlated with the starch content of the starter feed, whereas the response to starch was less positive before than after weaning.

The effects of feeding CRC diets on increasing withers and hip height indicate that the processing method may influence nutrient partitioning toward bone or fat deposition, which is probably due to differences in starch availability (Theurer, 1986; Owens et al., 1997). This was especially evident in heifers fed the CRC diet, as they had greater DMI, ADG, and structural growth in comparison to calves fed other diets, which is aligned with the results reported by Makizadeh et al. (2020). The higher blood glucose concentration in dairy calves fed the CRC diet could have a sparing effect on AA, diverting them into greater structural growth rather than entering the gluconeogenesis pathway (Young, 1977). Therefore, heifers fed CRC seem to have greater AA available for growth. Regardless of the mechanism, greater withers height is indicative of higher milk production after first calving as suggested earlier (Kertz et al., 1998).

The total-tract digestion of OM (+10%) and starch (+9%) were greater for CRC than for the DRC and FGC diets. In corn processing methods, variations in starch digestion is parallel to changes in OM digestion. The pelleting of grains or diets increases the amount of gelatinized starch granule during the heating process (Waigh et al., 2000; Crochet et al., 2005). In the crumbling process, the feed mixture is heated at 75 to 87°C in the conditioner and this processing increases the content of gelatinized starch (Abdollahi et al., 2018). In our study, feeding crumbled corn rather than FGC and DRC diets enhanced the apparent starch digestibility in heifers. These findings are in line with the study of Corona et al. (2005), who concluded that heat treatments (steam-flaking) could increase starch digestibility compared with the mechanically processed corn (grinding and dry rolling). Soltani et al. (2020) reported that pellets conditioned at 80°C for a maximum of 4 min had a greater starch apparent digestibility in comparison to the control diet due to the extensive gelatinization and solubility of starch in the rumen and total gastrointestinal tract. In addition, heifers fed FGC had greater starch digestibility than those receiving DRC (+4%), which may be associated with the mean particle size of corn. In addition, fecal starch concentration was lower for CRC compared with DRC diets. Particle size, grain processing, and feed intake may influence starch digestion and fecal starch concentration in feedlot cattle (Zinn et al., 2007) and dairy calves (Dennis et al., 2017) fed high corn grain-based diets. Inverse relationship between total-tract starch digestibility and fecal starch concentration supports findings from Dennis et al.

(2017) suggesting that fecal starch concentration may have some promise as an indicator of starch digestibility in the weaned calf. Fecal starch concentration may be influenced to a greater extent by DMI than total-tract starch digestibility in weaned calves (9 to 12 wk of age; Dennis et al., 2017). Khan et al. (2008) reported higher daily fecal starch output with greater DMI in 9-wk-old weaned calves fed pelleted calf starters diets with 25% starch based on barley, corn, oats, and wheat. However, a similar relationship was not observed in 13-wk-old weaned dairy calves in the current trial.

In our study, feeding behavior (i.e., standing, lying, and eating, min/22 h) was not affected by treatments. Beauchemin et al. (2001) and Harvatiné et al. (2002) reported that processing of barley and corn grain had no effect on eating and rumination time in steers and dairy cows. Feeding behavior may directly affect the performance of dairy calves, and the learned behavior patterns may persist and affect welfare in the long term (Miller-Cushon and DeVries, 2015). For example, feeding behavior could potentially be applied for characterization of infrequent meals, which are related to the incidence of SARA (González et al., 2012). In the current study, the tendency for increasing rumination time in CRC and DRC diets may be associated with the larger geometric size of the CRC and DRC compared with FGC, which can increase retention time in the rumen, thus leading to increased rumination time (Savari et al., 2018). Similarly, Knowlton et al. (1996) reported greater rumination time for cattle fed diets containing cracked corn (3.26 cm particle size) compared with feeding finely ground corn (0.83 cm particle size). One may speculate that the greater time spent ruminating by heifers fed CRC and DRC diets, in addition to being stimulated by the greater particle size, also could be a protective mechanism against rumen acidosis when highly fermentable starch sources are fed. However, the relationship between corn grain processing and feeding behavior needs to be investigated further in dairy calves.

The increased molar proportion of propionate and decreased acetate-to-propionate ratio in heifers consuming corn grain processed with heat and moisture, as reported in previous studies (Ekinci and Broderick, 1997; Dann et al., 1999; Malekkhahi et al., 2021), is probably due to greater ruminal starch degradability. Different molar percentages of individual VFA in the rumen (a higher propionate instead of acetate) of heifers fed CRC partly explain improved ADG from an energy efficiency stance compared with the FGC and DRC diets. Propionate is the main glucogenic VFA and its energy supply is greater than acetate on a molar basis and therefore has greater potential to improve animal performance. Recently, Soltani et al. (2020) reported

that the molar proportion of propionate increased numerically in calves fed pelleted starter with 4-min retention time in comparison to the control (36.5 vs. 34.1 mol/100 mol, respectively), which corresponded to the higher ADG on d 57 to 70 of postweaning.

Blood glucose and IGF-I concentrations increased when heifers were fed the CRC diet. Similarly, higher glucose concentrations were also reported after substituting steam-flaked with ground corn in calves' diet (Makizadeh et al., 2020). Higher blood glucose concentrations were indicative of greater starch availability in animals receiving the CRC diet, which is consistent with greater propionate proportion in the rumen. Propionate is the main precursor of glucose in ruminants (Huntington, 1997). The key metabolic regulator for growing animals is IGF-1, which fosters nutrient uptake and cellular growth (Vacher et al., 1995). As BW gain increases, the plasma concentration of IGF-1 also rises, which is aligned with improved skeletal growth in heifers fed CRC in the present study. However, the IGF-1 concentration was not different among treatments in our previous study (Soltani et al., 2020), which investigated the effects of conditioner retention time during the pelleting process of starter feed in dairy calves. Plasma urea N concentration has linear relationship with dietary CP intake, ruminal degradability, and resultant ruminal NH_3 concentration in cattle (Broderick and Clayton, 1997; Lohakare et al., 2012). Although we did not measure ruminal NH_3 concentration and urinary N excretion, it is possible that heifers fed CRC (i.e., a greater starch digestibility) had more efficient capture of ruminal N resulting in lower ruminal NH_3 concentration, and lower urinary N excretion. This is supported by lower plasma urea N as observed for heifers fed CRC compared with DRC diets. DePeters and Ferguson (1992) reported that plasma urea N may be promising as an indicator of N capture in the rumen because of its positive correlation with ruminal NH_3 -N concentrations. Moreover, a strong linear relationship between plasma urea N and urine N excretion was identified in a previous study (Kohn et al., 2005).

CONCLUSIONS

Feeding crumbled corn improved ADG and final BW compared with dry rolled and finely ground corn and results are probably attributed to greater total-tract starch digestibility, molar proportion of ruminal propionate, and circulating plasma glucose concentrations. However, no differences were observed on growth performance in dairy heifers fed diets based on dry-rolled and finely ground corn. Based on the results observed in this study, feeding crumbled corn is effective at improving starch digestibility, and withers and hip heights

in young dairy heifers, which could be favorable in replacement heifer rearing program. The reasons for the lack of effects on growth performance between finely ground and dry-rolled corn are not clear, but a further evaluation on the effects of particle size and processing method on dairy heifer performance is warranted.

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