R. Bras. Zootec., 53:e20230140, 2024
https://doi.org/10.37496/rbz5320230140

Forage crops
Full-length research article

Revista Brasileira de Zootecnia

Brazilian Journal of Animal Science
e-ISSN 1806-9290
www.rbz.org.br

Effect of processing method of rehydrated flint corn grain silage on finishing performance of crossbred Angus × Nellore bulls

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Received: December 5, 2023
Accepted: April 15, 2024

How to cite: Piran Filho, F. A.; Bragatto, J. M.; Parra, C. S.; Silva, S. M. S.; Pinto, R. C. C.; Moraes, A.; Santos, T. C.; Jobim, C. C.; Owens, F. and Daniel, J. L. P. 2024. Effect of processing method of rehydrated flint corn grain silage on finishing performance of crossbreed Angus × Nellore bulls. Revista Brasileira de Zootecnia 53:e20230140. https://doi.org/10.37496/rbz5320230140

Editors:
Gustavo José Braga
Luiz Felipe Ferraretto

ABSTRACT - This trial was designed to evaluate the effect of processing method of rehydrated corn grain silage (RCGS) on feed intake, performance, carcass traits, feeding behavior, rumen morphology, and blood metabolites of cattle in the finishing phase. Thirty-eight F1 Angus × Nellore bulls (365±22 kg) raised under grazing conditions were housed in individual pens (2 × 4 m) for the feeding trial. At the end of the adaptation period, animals were weighed after a 16-h fast, blocked by shrunk body weight, and randomly assigned to one of two dietary treatments: GRC, consisting of RCGS that was ground before ensiling using a hammer mill with a uniform 8-mm screen (1.52 mm geometric mean particle size); and RRC, consisting of RCGS that was rolled before ensiling in a roller mill mounted in a bagging machine (2.18 mm geometric mean particle size). Diet ingredients were mixed manually twice daily, at 09:00 and 15:00 h, and offered as total mixed rations in amounts approximately 50 g/kg in excess of daily intake. The experimental diets contained a forage:concentrate ratio of 130:870 g/kg, with 644 g/kg of RCGS. The GRC resulted in greater daily variation in dry matter intake, total-tract digestibility (dry and organic matter), fecal pH, rumen papillae width, and lower first meal duration, meal length, fecal starch, and rumen papillae height than the RRC. However, grinding or rolling RCGS did not affect dry matter intake, growth performance, carcass traits, or health (liver abscesses, ruminitis, serum D-lactate) of finishing beef cattle. Therefore, the processing equipment to make RCGS might be preferable based on equipment availability, milling yield, energy consumption, and diet composition.

Keywords: feed efficiency, feedlot, grain processing, starch digestibility

1. Introduction

Corn grain is a major source of starch in feedlot diets (Samuelson et al., 2016; Pinto and Millen, 2019). In a survey of Brazilian nutritionists, corn was the grain most cited (i.e., 97%) as an energy source in finishing diets, with all corn grain being considered flint (Silvestre and Millen, 2021). However, the endosperm protein matrix that surrounds the starch granules represents a barrier to the digestion of starch (Owens et al., 1986). Ensiling high-moisture (HMC) or rehydrated corn gain (RCGS) is an efficient strategy to improve starch digestibility and feed efficiency (FE) in feedlot cattle (Owens and Basalan, 2013), especially for flint corn grain (Jacovaci et al., 2021).

The optimal efficiency of feedlot diets containing corn grain silage is attained when starch digestion is maximized without causing ruminal acidosis (NASEM, 2016; Gouvêa et al., 2019). Digestibility of RCGS is primarily affected by moisture content, storage period, and particle size, which taken together have additive effects (Gomes et al., 2020). A moisture content of 350 g/kg and a storage period of at least two months have been recommended to improve the preservation and digestion of flint RCGS (da Silva et al., 2019; Fernandes et al., 2021; Gomes et al., 2020); however, the ideal particle size for RCGS from flint corn grain remains debatable (Gouvêa et al., 2019). In finishing high-concentrate diets, large grain particles might decrease starch digestion and FE, whereas fine particles may depress dry matter intake (DMI) and reduce average daily gain (ADG), due to the high load of rumen degraded starch. Summarizing 15 finishing cattle trials, Owens and Thornton (1976) concluded that DMI decreased linearly by about 0.4% for each 10 g/kg increase in moisture content of HMC from 230 to 300 g/kg moisture. Based on DMI depression, the authors stated that acidosis should be of concern with finely ground HMC.

Currently in Brazil, many beef farmers are ensiling rehydrated corn grain after rolling, due to the higher milling yield and reduced energy costs of rolling instead of grinding, and the availability of bagging machines mounted with roller mills. Meanwhile, the geometric mean particle size (GMPS) of rolled RCGS is often larger than those ground RCGS. Therefore, we hypothesized that processing RCGS more intensively would improve the total-tract digestibility and, in turn, the performance of feedlot cattle. The objective of this work was to evaluate the effect of processing method of flint RCGS on the total-tract digestibility and performance of finishing beef cattle.

2. Material and Methods

All animal care and handling procedures were approved by the Ethics Committee on Animal Use (protocol number 5843150421). The experiment was carried out in Maringá, PR, Brazil (23º 25' S; 51º 57' W, 550 m elevation).

2.1. Preparation of corn grain silages

Pre-dried whole shelled flint corn (790 g/kg of endosperm vitreousness determined by manual dissection; Dombrink-Kurtzman and Bietz, 1993) was processed (ground or rolled) and rehydrated to form the RCGS. The ground RCGS consisted of dry whole corn grain that was ground using a hammer mill (3,550 rpm) with a uniform 8-mm screen (Maquinas Pereira, Londrina, Brazil). The rolled RCGS was the same batch of dry corn grain that was processed in a roller mill mounted in a bagging machine (SEGU30, Multiagro, Porto Alegre, Brazil). The bagger had a single pair of corrugated rolls with a differential speed of 35% and a 1-mm gap between rolls. Grain processed through each mill was rehydrated to 350 g/kg moisture by weighting the processed grain and water in a mixer wagon (VMN 6.0 PA, Nogueira S/A Máquinas Agrícolas, São João da Boa Vista, Brazil) and mixing for 5 min. After rehydration, each processed grain was packed in separate bag silos (1.8 m diameter, Pacifil, Sapiranga, Brazil) using a bagging machine (SEGU 30, Multiagro Implementos Agrícolas, Porto Alegre, Brazil) and stored for 83 days before starting the feeding trial.

The distribution of particles of RCGS at silo opening (Table 1) was measured for dried (72 h in an oven at 55 °C) samples using a horizontal shaker (Ro-Tap; Solotest, São Paulo, Brazil). Approximately 120 g of dry sample was shaken for 10 min. The GMPS and geometric standard deviation (GSD) of RCGS was calculated according to ASABE (2008; method S319.4). Samples of RCGS were also analyzed for fermentation end products and pH as described in Gomes et al. (2020).

2.2. Animals, facilities, sanitary protocol, diets, and feeding

Thirty-eight 19-month-old crossbred bulls [F1 Angus × Nellore; 380±23 kg; shrunk body weight (SBW) 365±22] raised under grazing conditions were housed in concrete individual partially covered pens (2 × 4 m) equipped with feed bunk and water trough. During the trial, ambient temperatures ranged from 20.5 °C (average minimum) to 30.0 °C (average maximum) and average humidity of 0.76. Before

entering the experiment, the animals received two doses of vaccine against clostridia (Covexin 9, MSD Saúde Animal, São Paulo, Brazil), an application of oral dewormer based on albendazole (Valbazen® 10 Cobalto, Zoetis, Campinas, Brazil), and a pour on based on abamectin 0.5% (FRIGOBOI, J.A. Saúde Animal, Patrocínio Paulista, Brazil). At the beginning of finishing, the animals received another application of pour on and dewormer.

Table 1 - Composition and particle size distribution (mean ± standard deviation) of rehydrated corn grain silage (RCGS)

Item	Ground RCGS	Rolled RCGS
Dry matter (DM; g/kg as fed)	635±10.1	638±11.0
Nutrients (g/kg DM)		
Crude protein	88.9±1.60	90.4±0.90
Ash	14.1±0.20	14.6±0.50
Ether extract	40.3±0.20	41.1±0.40
Neutral detergent fiber	103±7.80	105±7.50
Starch	709±8.90	708±8.00
Lactic acid	12.4±5.22	12.3±0.324
Acetic acid	14.2±3.00	10.7±2.61
Ethanol	6.96±0.873	4.19±0.439
NH_3-N (g/kg N)	27.9±6.72	22.0±6.33
pH	3.99±0.065	3.93±0.058
Particle size distribution (g/kg DM)		
8.00 mm	0.60±0.60	5.50±1.00
4.75 mm	4.80±0.50	34.8±4.70
2.00 mm	349±8.90	678±22.0
1.18 mm	379±17.0	153±13.9
0.60 mm	162±11.1	74.4±9.80
0.30 mm	70.8±7.30	37.4±2.80
Pan	33.8±3.2	16.9±2.80
GMPS (mm)[1]	1.52±0.15	2.18±0.18
GSD (mm)[1]	1.16±0.14	1.63±0.17

[1] Geometric mean particle size (GMPS) and geometric standard deviation (GSD) were calculated according to ASABE (2008; method S319.4) after measuring particle size distribution using a Ro-Tap Sieve Shaker.

Animals had free-choice access to water and feed, offered as a total mixed ration (TMR). The TMR ingredients were weighted and mixed manually twice daily, immediately before each feeding at 09:00 and 15:00 h, in amounts approximately 50 g/kg in excess of daily intake. During the first seven days after the arrival of the animals, a high-forage (550 g/kg) diet was provided to acclimate them to the facilities. The adaptation dietary program consisted of *ad libitum* feeding of three step-up adaptation diets for 18 days (six days each step). The dietary concentrate level increased from 450 to 630 g/kg in step 1, 630 to 710 g/kg in step 2, and 710 to 870 g/kg in step 3, on dry matter (DM) basis. Ingredients used in the adaptation diets included corn silage, sugarcane bagasse, dry ground corn grain, ground RCGS, rolled RCGS, soybean hulls, corn gluten feed, soybean meal, urea, limestone, and mineral mix. During this adaptation period, all bulls received the same diet.

At the end of the adaptation period, animals were weighed after 16 h of feed fast (overnight) and 2 h of water fast, and blocked by SBW (two animals per block). Within each experimental block, animals were randomly assigned to one of the two dietary treatments: GRC, consisting of RCGS that was ground before ensiling using a hammer mill with a uniform 8-mm screen (1.52 mm geometric mean particle size); and RRC, consisting of RCGS that was rolled before ensiling in a roller mill mounted in a bagging machine (2.18 mm geometric mean particle size) (Table 2). On weighting day, feeding frequency was increased to three times per day, to prevent rapid and large intake of the high-grain diet after fasting. Dietary treatments were compared during the finishing period of 69 days.

Table 2 - Composition (mean ± standard deviation) of experimental diets

Item	Treatment[1]	
	GRC	RRC
Ingredients (g/kg dry matter (DM))		
Sugarcane bagasse	130	130
Ground RCGS	644	-
Rolled RCGS	-	644
Corn gluten feed	190	190
Urea	10.0	10.0
Limestone	8.00	8.00
Mineral mix[2]	18.0	18.0
Nutrients (g/kg DM)		
Crude protein	130±3.00	131±3.60
Ash	47.3±1.80	47.6±2.00
Ether extract	32.4±2.10	32.9±2.80
Neutral detergent fiber (NDF)	241±15.5	240±15.1
Starch	491±14.8	491±15.6
Roughage NDF	104	104
peNDF > 8 mm[(3)]	15.4	19.2
PSPS particle size distribution (g/kg as fed)[4]		
8-19 mm	64.0±2.40	80.0±2.20
4-8 mm	162±7.70	170±11.8
Pan	774±5.00	750±9.60

[1] GRC - diet containing ground rehydrated corn grain silage; RRC - diet containing rolled rehydrated corn grain silage.
[2] Composition per kilogram: 160 g Ca, 64 mg Co, 800 mg Cu, 300 mg F, 48 mg I, 800 mg Mn, 24 g Mg, 110 g Na, 30 g P, 22 g S, 12 mg Se, 2,400 mg Zn, and 1,500 mg of monensin sodium.
[3] peNDF>8 mm - physically effective NDF calculated as the NDF content of total mixed ration (TMR) multiplied by the proportion of TMR > 8 mm.
[4] PSPS - Penn State Particle Separator. No particle was retained on the 19-mm sieve.

2.3. Sampling and measurements

Feed intake was measured daily by weighing offered feed and orts, and the amount offered was adjusted allowing for a minimum of 50 g/kg of orts during the experiment. Daily DMI fluctuation was calculated as the difference between the DMI on the current day and the DMI on the previous day, expressed as a proportion of the DMI on the previous day (Bevans et al., 2005). Offered diets and orts were sampled daily (250 g/kg of the orts and 10 g/kg of the offered diets), composed by animal, and analyzed to estimate the chemical composition of the diet consumed. After sampling, orts were discarded.

The ADG was determined as difference between the initial and final SBW and divided by the number of days on feeding. Feed efficiency was calculated as ADG divided by DMI (FE = ADG/DMI). From the individual DMI and ADG data, diet net energy was estimated using the calculation method described by Zinn and Shen (1998). Energy requirement for gain was calculated as: Eg (MJ/d) = 4.184 × (0.0493 × ((BW × 478/FW)$^{0.75}$) × ADG$^{1.097}$), in which BW is mean body weight, 478 is standard reference weight, and FW is final weight. Energy requirement for maintenance was calculated as: Em (MJ/d) = 4.184 × 0.077 × BW$^{0.75}$. Diet net energy for maintenance was estimated by the equation: NEm (MJ/kg DM) = 4.184 × ((−b − (b^2 − 4ac)$^{0.5}$)/2a), in which: a = −0.877 × DMI, b = (0.877 × (Em/4.184)) + (0.41 × DMI) + (Eg/4.184), and c = −0.41 × (Em/4.184). Diet net energy for gain was calculated as: NEg (MJ/kg DM) = 4.184 × ((0.877 × (NEm/4.184)) − 0.41). Diet metabolizable energy was calculated as: ME (MJ/kg DM) = ((23.8573 × NEm/4.184 + 2.3974 × (NEm/4.184)2 + 24.7761) × 0.0362) × 4.184, whereas ME intake (MJ/d) was computed as ME × DMI.

On days 30 and 31 of the finishing period, individual feeding behaviors (eating and ruminating time, meal frequency, first meal duration, meal length, meal size, meal interval, and intake rate) were measured during two consecutive 48-h periods by visual evaluation every 5 min by trained evaluators (Maekawa et al., 2002). Total chewing time was calculated as the sum of time spent eating

and ruminating. A meal was defined by at least two consecutive 5-min ingestion events followed by at least 10 min of idling, rumination, or water intake. Meal length was obtained by dividing eating time by number of meals. Meal size was estimated by dividing DMI by number of meals. Intake rate was calculated by dividing DMI by eating time.

Particle sorting index (PSI) was determined on days 15 to 19 and 53 to 57. Samples of offered TMR and individual orts were sieved using the Penn State Particle Separator (PSPS; 19, 8, 4 mm and pan; Heinrichs, 2013). The PSI was calculated for particles retained on each PSPS sieve (as fed basis) and diet neutral detergent fiber (NDF), in which values lower than 1 indicate selective refusal, those greater than 1 indicate preferential intake, and those equal to 1 indicate no sorting (Leonardi and Armentano, 2003).

Total-tract digestibility was evaluated twice during the finishing period, using indigestible NDF (iNDF) as an internal marker (Huhtanen et al., 1994). Fresh stools were sampled manually every morning and evening during days 15 to 19 and 53 to 57 of the finishing period. Fecal samples of each animal in each collection period were stored at −20 °C in separate plastic bags. After thawing, samples were composited on an equal wet weight basis for DM and iNDF determination. Digestibility was calculated using intake data recorded on days of fecal sampling. Additionally, fecal score and pH were recorded. Fecal consistency score (1 to 5; Waldner et al., 2007) was recorded after each feeding by three trained evaluators. Fecal pH was measured using an extract prepared by mixing 15 g of fresh feces with 100 mL of distilled water (Ireland-Perry and Stallings, 1993) with pH recorded after 2 min (pH meter model Tec5, Tecnal, Piracicaba, Brazil).

Blood samples were collected from the jugular vein of each animal at 6 ± 1 h after feeding on day 68 of finishing, in tubes without anticoagulant for serum and with anticoagulant (K_3EDTA) for plasma. After blood collection, the tubes were centrifuged at 4,000 × *g* for 15 min at 4 °C to obtain serum and plasma, respectively. Commercial kits were used for analysis of plasma glucose (Glicose PP, Gold Analisa Diagnóstica Ltda, Belo Horinzonte, Brazil), plasma urea (Ureia PP, Gold Analisa Diagnóstica Ltda, Belo Horinzonte, Brazil), and serum D-lactate (D-Lactate Colorimetric Assay Kit, Elabscience, Houston, Texas, USA).

At the final weighing on day 69 of the finishing (after 16 h of overnight fast), carcass traits of live animals were evaluated by ultrasound (Aloka SSD500; 17-cm, 3.5-MHz probe). Ribeye area and back fat thickness were measured between the 12th and 13th ribs transversally to the *longissimus* muscle. Marbling score (1 = nil to 10 = abundant) was recorded from the 11th to 13th rib longitudinally to the *longissimus* muscle. *Biceps femoris* fat thickness was also recorded. A single trained technician scanned all animals, with images analyzed using Bia Pro Plus software (Designer Genes Technology). Afterward, animals were transported 110 km to a commercial abattoir and slaughtered according to animal welfare and slaughter practices established by the local sanitary inspection.

After evisceration, hot carcass weight (HCW) was recorded, and dressing was calculated as HCW/SBW. Liver abscesses were scored according to incidence and severity as following: score 0 (without abscess), 1 (one or two abscesses with <2.5 cm or abscess scars), 2 (three to four abscesses <2.5 cm), and 3 (one abscess >2.5 cm or several small abscesses) (Brink et al., 1990). Rumen epithelium was scored according to the lesion incidence (0–10), in which zero indicated no lesions or abnormalities and 10, severe lesions all over the rumen wall (Bigham and McManus, 1975). After digesta removal, two fragments of 1 cm^2 were obtained from the rumen recess (ventral sac). One fragment was fixed in 10% buffered formalin for microscopic measurement. The other fragment was stored in cold phosphate buffer solution (pH 7.4, 4 °C) for macroscopic measurements within 48 h.

For the macroscopic measurements, 12 papillae were subsampled from the fragment, digitized with a scanner, and measured manually using the ImageJ software (ImageJ 1.8.0_172, National Institutes of Health, Bethesda, USA) to obtain: number of papillae/cm^2, papillae surface area, papillae height, and papillae width. Papillae number of the whole fragment was counted by two independent evaluators. The rumen surface area per cm^2 of wall was calculated as follows: rumen surface = wall surface − (number of papillae × 0.002) + (number of papillae × mean surface of papillae), in which 0.002 cm^2 (i.e., 0.02 × 0 .1) was the surface of the base of the papilla obtained by Daniel et al. (2006).

For microscopic analysis, the fragment fixed in formalin was dehydrated in ethanol and xylene and embedded in paraffin. Sections (5 µm) were stained with hematoxylin and eosin to determine epithelium thickness, keratinized layer thickness, and nonkeratinized layer thickness. Twenty-five measures were performed at random locations of the epithelium on the histological slides from each animal. The images and analyses were performed using an Olympus BX41 microscope (400× magnification) coupled to a computer, through Motic imaging software plus 2.0 ML.

2.4. Laboratory analysis

Samples of feeds, TMR, orts, and feces were dried at 55 °C for 72 h in an oven and ground in a Wiley type mill with a 1-mm pore sieve. Sub-samples were analyzed for absolute DM (method 930.15; AOAC, 2000), ash (method 942.05; AOAC, 2000), crude protein (CP; method 984.13; AOAC, 2000), and ether extract (EE; method 920.29; AOAC, 1990). The content of organic matter (OM) was calculated as 1000 – ash. The NDF was assayed using filter bags (F57, Ankom) and a neutral detergent solution including thermostable amylase and sodium sulfite (method 2002.04; Mertens, 2002). The iNDF was determined by 288 h of *in situ* ruminal incubation (Huhtanen et al., 1994). The cannulated animals were Nellore bulls weighing 460 kg receiving a diet with 650 g of concentrate and 350 g of corn silage per kg of DM. Total starch (measured as starch + free glucose) content of feces, orts, ingredients, and TMR was determined enzymatically using a commercial assay kit (K-TSTA-100A, Megazyme International Ireland Ltd., Bray, Ireland; method 996.11, AOAC, 2007).

2.5. Statistical analysis

The data were evaluated for normality of residuals (Shapiro-Wilk test) and homogeneity of variances (Bartlett test). Afterward, data were analyzed using the Mixed procedure of SAS (Statistical Analysis System, version 9.4). Animal performance data were analyzed as a randomized complete block design with the following model:

$$yij = \mu + bi + \tau j + \varepsilon ij,$$

in which µ: overall mean, bi: random effect of block (i = 1 to 19), τj: fixed effect of treatment (j = GRC or RRC), and εij: residual error.

Liver abscess and ruminitis scores were compared by the Chi-square test. The experimental unit was the animal. Differences between treatments were declared if $P \leq 0.05$, and trends were presumed when $0.05 < P \leq 0.10$.

3. Results

Nutrient concentration was similar between ground and rolled RCGS, but GMPS was 43% greater for the RCGS processed in the roller mill (Table 1). Experimental TMR had similar composition of nutrients, whereas particle size distribution on the PSPS indicated a slightly coarser ration for RRC (Table 2).

Dietary treatments had no effect ($P>0.10$) on initial SBW, final SBW, DMI, ADG, FE, HCW, dressing, ribeye area, marbling score, back fat thickness, *biceps femoris* fat thickness, and liver abscess score (Table 3). However, the GRC induced greater DMI variation than the RRC ($P \leq 0.05$). The GRC also resulted in lower meal length and first meal duration than the RRC ($P \leq 0.05$; Table 4). Chewing (min/d) tended to be lower for GRC than RRC ($P<0.10$). Eating, ruminating, and chewing time, meal frequency, meal size, meal interval, intake rate, particle sorting index, and diet NDF sorting were similar between treatments ($P>0.10$).

Total-tract apparent digestibility of DM, OM, CP, EE, and starch, and fecal pH were higher ($P \leq 0.05$), while fecal starch was lower ($P \leq 0.05$) for GRC than RRC (Table 5). Apparent digestibility of NDF, fecal score, and diet energy content based on animal performance were similar between treatments ($P>0.10$).

Dietary treatments had no effect (P>0.10) on ruminitis score, number of papillae/cm^2 of rumen wall, papillae surface, rumen surface, epithelium thickness, keratinized layer thickness, and nonkeratinized layer thickness, but the GRC induced lower (P≤0.05) papillae height, and higher (P≤0.05) mean papillae width than the RRC (Table 6). Plasma glucose and serum D-lactate were similar (P>0.10) between treatments, whereas plasma urea concentration tended to be lower for GRC than RRC (P<0.10).

Table 3 - Performance, carcass traits, and liver abscess scores for finishing bulls

Item	Treatment[1]		SEM	P-value
	GRC	RRC		
Performance				
Initial shrunk body weight (kg)	412	413	6.7	0.848
Final shrunk body weight (kg)	543	544	10.5	0.918
Dry matter intake (kg/d)	11.2	11.2	0.33	0.869
Dry matter intake variation (g/kg DM)	87.2	68.9	6.26	0.046
Average daily gain (kg/d)	1.92	1.92	0.086	0.966
Feed efficiency	0.170	0.171	0.005	0.792
Carcass traits				
Hot carcass weight (kg)	301	306	6.1	0.584
Carcass dressing	0.555	0.562	0.0049	0.331
Ribeye area (cm^2)	84.1	85.2	1.93	0.699
Marbling score (0–10)	3.60	3.46	0.105	0.348
Back fat thickness (mm)	5.99	6.12	0.304	0.763
Biceps femoris fat thickness (mm)	7.96	8.20	0.353	0.639
Liver abscess frequency (n/19)[2]	0/19	1/19	-	-

DM - dry matter; NDF - neutral detergent fiber; SEM - standard error of the mean.
[1] GRC - diet containing ground rehydrated corn grain silage; RRC - diet containing rolled rehydrated corn grain silage.
[2] Liver abscess scores were not reported as only one small abscess was observed in one bull (P = 0.489 by Fisher's Exact test).

Table 4 - Feeding behavior and particle sorting index for finishing bulls

Item	Treatment[1]		SEM	P-value
	GRC	RRC		
Feeding behavior				
Eating (min/d)	167	186	9.1	0.138
Ruminating (min/d)	370	394	13.5	0.231
Chewing (min/d)	540	580	14.6	0.063
Chewing (min/kg DM)	49.6	52.2	1.88	0.333
Meal frequency (meals/d)	12.4	12.3	0.54	0.799
First meal duration (min)	29.9	41.4	3.08	0.012
Meal length (min/meal)	13.1	15.8	0.73	0.014
Meal size (g DM/meal)	922	987	57.1	0.428
Meal interval (min)	108	109	13.2	0.934
Intake rate (g DM/min)	68.8	64.2	3.99	0.425
Particle sorting index				
8-19 mm	1.04	1.02	0.008	0.314
4-8 mm	1.01	1.01	0.002	0.281
Pan	0.996	0.995	0.001	0.478
Diet NDF sorting index	1.01	1.01	0.002	0.760

DM - dry matter; NDF - neutral detergent fiber; SEM - standard error of the mean.
[1] GRC - diet containing ground rehydrated corn grain silage; RRC - diet containing rolled rehydrated corn grain silage.

Table 5 - Total-tract digestibility, fecal traits, and diet energy in finishing bulls

Item	Treatment[1]		SEM	P-value
	GRC	RRC		
Apparent total-tract digestibility				
Dry matter (DM)	0.746	0.728	0.046	0.009
Organic matter	0.763	0.743	0.045	0.003
Neutral detergent fiber	0.565	0.569	0.011	0.811
Crude protein	0.725	0.708	0.054	0.038
Ether extract	0.801	0.759	0.014	0.043
Starch	0.956	0.936	0.003	<0.001
Fecal traits				
Fecal score (1–5)	3.83	3.92	0.076	0.450
Fecal pH	6.20	5.93	0.060	0.003
Fecal starch (g/kg DM)	72.2	93.2	3.36	0.001
Diet energy (MJ/kg DM)[2]				
Net energy for maintenance	8.23	8.23	0.113	0.988
Net energy for gain	5.50	5.50	0.099	1.000
Metabolizable energy	12.3	12.3	0.13	0.990
ME intake (MJ/d)	139	137	4.1	0.723

SEM - standard error of the mean.
[1] GRC - diet containing ground rehydrated corn grain silage; RRC - diet containing rolled rehydrated corn grain silage.
[2] Energetics calculated based on animal performance (Zinn and Shen, 1998).

Table 6 - Rumen morphology and blood metabolites of finishing bulls

Item	Treatment[1]		SEM	P-value
	GRC	RRC		
Rumen morphology				
Macroscopy				
Ruminitis score (0–10)	0.368	0.500	0.114	0.433 (χ^2)
Number of papillae (n/cm^2)	38.6	38.3	2.63	0.939
Mean papillae surface area (cm^2)	0.402	0.396	0.026	0.865
Mean papillae height (cm)	1.06	1.18	0.420	0.042
Mean papillae width (cm)	0.376	0.331	0.014	0.034
Rumen surface area (cm^2/cm^2 of wall)	15.9	15.8	1.09	0.985
Microscopy				
Epithelium thickness (µm)	104	105	3.2	0.758
Keratinized layer thickness (µm)	20.7	20.2	0.84	0.700
Nonkeratinized layer thickness (µm)	83.1	84.9	3.32	0.691
Blood metabolites				
Plasma glucose (mg/dL)	77.9	79.9	3.21	0.668
Plasma urea (mg/dL)	26.9	30.0	1.25	0.086
Serum D-lactate (mmol/L)	1.20	1.30	0.165	0.685

SEM - standard error of the mean.
[1] GRC - diet containing ground rehydrated corn grain silage; RRC - diet containing rolled rehydrated corn grain silage.

4. Discussion

Early research has examined the effects of particle size of HMC (prepared with US dent corn) on cattle performance (Secrist et al., 1995; Secrist et al., 1996; Macken et al., 2006; Coulson et al., 2021), but this present study is the first to examine the effects of grinding or rolling dried flint corn to prepare RCGS for finishing feedlot cattle. As expected, RCGS that was rolled before ensiling had greater particle size than RCGS that was ground in a hammer mill with a uniform 8-mm screen. The GMPS of the ground RCGS (1.52 mm) was at the same magnitude of the mean value observed for dry-ground corn in US

feedlots (1.82 mm), but our rolled RCGS (2.18 mm) was noticeably finer than the mean dry-rolled corn surveyed in US feedlots (4.53 mm; Schwandt et al., 2015). Approximately 713 g/kg of the rolled RCGS particles were retained above the 2-mm screen but below the 8-mm screen (whole kernel), whereas only 354 g/kg of ground RCGS particles were retained above a 2-mm screen. Such differences in GMPS and particle distribution led to dissimilar responses in feeding behavior, DMI variation, total-tract digestibility, rumen papillae morphology, and plasma urea concentration. However, cattle performance remained unchanged by milling method.

In a previous study, we demonstrated that grinding, rather than rolling, flint RCGS increased *in situ* ruminal DM degradation by approximately 15% (Gomes et al., 2020). In the current trial, *in vivo* total tract-digestibility of starch and DM were approximately 20 g/kg greater for GRC than RRC. Whether increased surface exposure during fermentation of the more finely processed grain would complement the particle size effect on digestibility is uncertain. In contrast, Owens et al. (2016) reported in a data analysis that the total-tract starch digestion was weakly associated with ruminal starch digestion in HMC diets for feedlot cattle, but their dataset for HMC was small (n = 6). In our study, a greater ruminal degradability of starch in GRC is further supported by alterations in DMI variation, feeding behavior, plasma urea concentration, and rumen papillae morphology.

Total-tract starch digestibility values observed in the current study were lower than that found by Jacovaci et al. (2021), which reported 0.99 of starch digestibility for cattle fed diets containing ensiled corn grain. Differences in total-tract starch digestibility among studies may be due to diet composition, grain vitreousness, moisture, length of storage, grain particle size, and feed intake level, which ultimately affects passage rate. In our trial, DMI was around 23.5 g/kg BW, whereas in the meta-analysis of Jacovaci et al. (2021), DMI was on average 20.4 g/kg BW in animals fed diets containing ensiled corn grain.

Although DMI was similar between treatments, feeding behavior was altered by milling method in our study. Likewise, cattle fed GRC had greater DMI variation. Such responses strongly suggest a greater ruminal starch fermentability for GRC, which might have increased the portal flux of propionate, and probably altered liver signaling to brain feeding centers. In high-grain diets with a high proportion of ensiled corn as in the current trial, propionate is likely the major anaplerotic metabolite of the tricarboxylic acid cycle within meals (Allen, 2020). Propionate may stimulate greater oxidation of the existing pool of acetyl-CoA increasing hepatic energy charge that presumably could generate a satiety signal according to the hepatic oxidation theory (Allen, 2020). In fact, the GRC induced shorter meal length and first meal duration than RRC. Additionally, more available energy in the rumen often increases microbial protein synthesis and decreases ruminal ammonia and blood urea concentrations (Hristov et al., 2019). As DMI and diet CP were similar among treatments, a tendency of lower plasma urea concentration may have resulted from greater ruminal starch digestion for the GRC.

Recently, Pereira et al. (2021) found that reduced daily DMI variation was related to greater ADG and carcass weight, and lower rumenitis scores, indicating that high DMI fluctuation had adverse effects on growth performance potentially associated with an increased incidence of metabolic disorders. In our study, RCGS milling method did not change serum D-lactate, liver abscess, and ruminitis scores. However, rumen papillae of cattle fed GRC were wider and shorter, which may have reflected a greater ruminal volatile fatty acids (VFA) load and its consequences on epithelium proliferation and differentiation, and mucosal blood flow (Tamate et al., 1974; Gabel et al., 2002; Resende-Junior et al., 2006).

Despite the differences in total-tract digestion of starch, CP, EE, and total OM in favor of GRC, these changes were not translated into greater performance, and cattle fed GRC or RRC had the same FE. Secrist et al. (1995) also observed no effect of grinding or rolling HMC on DMI, ADG, FE, and carcass characteristics of feedlot cattle. A following study by the same group found tendencies of greater DMI and ADG as particle size of HMC increased (GMPS from 1.28 to 2.12 mm), without changes in FE and nutrient digestibility (Secrist et al., 1996).

More recent studies with diets containing corn grain coproducts also showed no or slight advantages of rolled over ground HMC in fishing diets. Comparing ground (GMPS 0.484 mm) or rolled (GMPS 2.90 mm)

HMC in diets with 250 g/kg of wet corn gluten feed (DM basis), Macken et al. (2006) found similar DMI, ADG, FE, fecal starch, and carcass traits. On the other hand, Coulson et al. (2021) observed that HMC processed with a roller mill (GMPS 2.87 mm) improved FE in finishing cattle by 4.7% compared with HMC processed in a hammer mill (GMPS 2.25 mm) in diets containing 200 g/kg DM of wet distillers with solubles. Starch digestibility and beef cattle performance have not always been correlated in the literature (Lundy et al., 2015). Moreover, the responses to particle size of ensiled corn might diverge between feedlot cattle and lactating dairy cows (Ferraretto et al., 2013), likely due to a combination of or interactions among various factors, including shorter retention time in the rumen and large intestine with higher DMI and fiber content in dairy diets (Owens et al., 2016). Whether benefits of reducing the particle size of grain in diets for lactating cows reflects greater sensitivity to ruminal acidosis or a greater impact on DMI on growing cattle than lactating cows remains unclear.

In our experimental conditions, the RRC diet likely increased the amount of starch flowing to the intestines. Although the post-ruminal starch digestion may not have completely compensated for lower ruminal starch fermentation (which led to a lower total-tract digestion), shifting site of starch digestion from the rumen to the small intestine might have reduced the risk of subclinical acidosis and increased energetic efficiency (Owens et al., 2016). If cattle fed GRC experienced subclinical acidosis, it may not have been clearly established in this study as compared with diets containing more ensiled corn grain or less roughage. Energetic efficiency with which starch is used by cattle varies with site of starch digestion, being higher for starch digested to glucose absorbed from the small intestine (energetic efficiency ~0.97) than for starch fermented in the rumen (energetic efficiency ~0.80), due to the greater loss of energy as heat and methane in the rumen (Owens et al., 1986; McLeod et al., 2001; Huntington et al., 2006). Although Kreikemeier et al. (1991) observed that 6 to 8% of the starch infused into the abomasum escaped digestion in the small intestine and passed through the ileum as unpolymerized glucose, in our study, dietary level of starch (about 500 g/kg DM) and post-ruminal starch digestibility may have offset differences from ruminal starch degradability. Previous literature suggests that post-ruminal starch digestibility is typically high for corn that has been ensiled (Szasz et al., 2007; Owens et al., 2016). Therefore, the intestinal starch digestion of RRC might have been sufficiently high in our bulls to secure similar ADG and FE despite having a lower total-tract starch digestibility than GRC.

Particle size of processed grains is greatly influenced by the combination of the milling setting (e.g., motor power, rotation per minutes, screen, etc). Hence, corn grain particle size distribution should be monitored to avoid under or overprocessing when producing RCGS. Practical goals for processing HMC in US feedlots target less than 25 g/kg of whole kernels and less than 200 g/kg of particles <1 mm (Hicks and Lake, 2006). In our study, both rolled and ground RCGS had less than 10 g/kg whole kernels while fine particles (<1.18 mm) were 129 and 267 g/kg, which seem particle distributions of bordering under or overprocessing in rolled and ground grain, respectively. Therefore, processing corn grain more finely than the ground RCGS used in this study may increase the risk of digestive disorders in diets with high proportion of RCGS, whereas processing less intensively to obtain coarser grain than our rolled RCGS might decrease starch digestion and make rehydration difficult at ensiling (i.e., increase the chance of water percolation).

5. Conclusions

Reducing the geometric mean particle size of RCGS from 2.18 mm (rolled) to 1.52 mm (ground) failed to influence performance of finishing cattle. Hence, RCGS processing method might be selected based on other aspects of the production system, such as availability of machinery and equipment, processing yield, and diet composition. Considering that the particle size of processed grains is greatly influenced by the combination of the milling setting, the particle size distribution should be monitored to avoid under or overprocessing the grain when producing RCGS.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization: Daniel, J. L. P. **Formal analysis:** Piran Filho, F. A.; Bragatto, J. M.; Parra, C. S.; Silva, S. M. S.; Pinto, R. C. C.; Moraes, A. and Daniel, J. L. P. **Funding acquisition:** Daniel, J. L. P. **Investigation:** Piran Filho, F. A.; Bragatto, J. M.; Parra, C. S.; Silva, S. M. S.; Pinto, R. C. C. and Moraes, A. **Methodology:** Santos, T. C.; Jobim, C. C.; Owens, F. and Daniel, J. L. P. **Project administration:** Daniel, J. L. P. **Resources:** Santos, T. C.; Jobim, C. C.; Owens, F. and Daniel, J. L. P. **Visualization:** Santos, T. C.; Jobim, C. C. and Owens, F. **Writing – original draft:** Piran Filho, F. A. **Writing – review & editing:** Daniel, J. L. P.

Acknowledgments

We thank all the members of the Grupo de Estudos em Silagem e Feno (GESF; Universidade Estadual de Maringá (UEM), Maringá - PR, Brazil) and the employees of the Fazenda Experimental de Iguatemi (UEM) for all their support in carrying out this study. We thank the Coordenação de Aperfeicoamento de Pessoal de Nível Superior - Brazil (CAPES) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brasília - DF, Brazil, for the scholarships provided to the authors.

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