

Influence of bagging machine and roll type combinations on the conservation, processing, and starch degradability of rehydrated corn and sorghum grains

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Received: October 28, 2025
Accepted: March 10, 2026

How to cite: Melo, N. N.; Cordeiro, M. W. S. and Bernardes, T. F. 2026. Influence of bagging machine and roll type combinations on the conservation, processing, and starch degradability of rehydrated corn and sorghum grains. *Revista Brasileira de Zootecnia* 55:e20250211.
<https://doi.org/10.37496/rbz5520250211>

Editors:

Gustavo José Braga
João Luiz Pratti Daniel

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ABSTRACT - Five bagger configurations were evaluated for their effects on physical characteristics, fermentation, and starch degradability in corn (Exp. 1) and sorghum (Exp. 2) grain silages. Both experiments were conducted using five treatments, involving baggers with different nominal power ratings (60, 75, and 90 hp; designated as M-60, M-75, and M-90). The treatments consisted of the following configurations: M-60 equipped with a standard roll; M-75 and M-90 equipped with intermediate and coarse rolls for corn; and fine and intermediate rolls for sorghum. Three bags were produced for each treatment, for a total of 15 silos (experimental units) per experiment. Treatments were considered fixed effects, whereas bags nested within treatments were considered random effects. Means were compared using Tukey's test at 5%. The degree of grinding of corn and sorghum grains, as well as its effects on silage fermentation and starch degradability was assessed. No differences were observed in fermentation and microbial counts. In Exp. 1 (corn), M-60 + standard roll exhibited greater degradability (72.6%; $P = 0.02$). In corn, coarse rolls (M-75 and M-90) increased particle retention on 4.75 mm sieves and reduced particle retention on 1.70 and 1.18 mm sieves, resulting in an increase in geometric mean diameter (GMD; $P = 0.01$). In Exp. 2 (sorghum), intermediate rolls increased the proportion of larger particles, the GMD ($P = 0.003$), and the number of whole grain kernels, especially with M-90 ($P = 0.015$). Overall, for ensiling corn in silo bags, the M-60 + standard roll and the M-75 and M-90 + intermediate rolls are suggested, as these combinations enhance grain disruption and starch degradability. For sorghum, using fine rolls on the M-75 and M-90 baggers is recommended to improve grain fragmentation.

Keywords: grain processing, silo-bag, starch degradability

1. Introduction

Corn and sorghum grains are widely used in ruminant nutrition as major energy sources, primarily due to their high starch content (Huntington, 1997). However, the extent to which this nutrient can be effectively utilized depends not only on the physical and chemical structure of the grain but also on the processing methods applied (Oba and Allen, 2003; Rémond et al., 2004; Francis et al., 2023).

Advances in feed conservation strategies have promoted practices that integrate high milling efficiency with improved silage quality. In this context, Brazilian producers have increasingly adopted the ensiling of high-moisture or reconstituted grains following roller processing (Piran Filho et al., 2024), using systems that combine roller milling with storage in silo bags. Driven by greater milling efficiency and

higher operational throughput (tons per hour) (Bartosik et al., 2024; Piran Filho et al., 2024), this strategy also offers advantages inherent to silo-bag ensiling, including the rapid establishment of anaerobic conditions, reduced storage losses, flexibility regarding the location of silage preparation, and a wide range of storage capacities (Muck et al., 2020).

Cereal grain silage is associated with increased starch degradability (Owens et al., 1997). This effect occurs due to an associative interaction between grain processing and silage fermentation. First, processing promotes kernel disruption, thereby facilitating the breakdown of the protein matrix by silage microorganisms and endogenous grain enzymes (Junges et al., 2017). Second, processing influences starch degradation at the ruminal level (Rooney and Pflugfelder, 1986; Owens et al., 1986; Tedeschi et al., 2012). However, the magnitude of these effects can vary depending on the type of grain and the processing system used (Giuberti et al., 2014). In addition, uncertainties remain regarding the effectiveness of these systems in providing adequate grain grinding, especially in comparison with traditional methods, such as hammermill grinding. Many comparisons in the literature are based on the use of older equipment, which may underestimate the efficiency of modern systems, including improvements in processing uniformity, the proportion of disrupted grain particles, and the resulting impacts on starch degradability. The lack of information limits the development of optimized strategies, as milling intensity and uniformity significantly influence silage physicochemical properties, nutrient preservation, and processing costs.

Our hypothesis was that modern roller processing systems would promote a higher degree of grain breakage and improved starch degradability, resulting in differences in the physical and chemical properties of silages. Thus, the aim of this study was to evaluate five bagger configurations with respect to the degree of grinding of corn (Exp. 1) and sorghum (Exp. 2) grains, as well as their respective effects on silage fermentation and starch degradability.

2. Material and methods

2.1. Preparation of the silages and treatments

Two experiments, one with corn (Experiment 1) and another with sorghum (Experiment 2), were conducted at Santa Bárbara Farm, located in Terra Rica, PR, Brazil. The corn and sorghum hybrids used were Pioneer 3282® and Nused 420®, respectively.

The three baggers used in the study, all from a single manufacturer, are presented in Table 1 along with their key technical specifications. For standardization purposes, are referred to throughout the manuscript as M-60, M-75, and M-90, corresponding to the nominal power (hp) recommended by the manufacturer to ensure optimal machine performance. The characteristics of the rollers mounted on the baggers are indicated in the treatment descriptions, in parentheses, using the following format: number of teeth per inch and inter-roll spacing (roll gap) in millimeters (mm).

In the corn grain experiment, the sets evaluated configurations consisted of: i) M-60 + standard roll (7 teeth per inch; 0.40 mm), ii) M-75 + intermediate roll (6 teeth per inch; 0.45 mm), iii) M-75 + coarse roll (4 teeth per inch; 0.65 mm), iv) M-90 + intermediate roll (6 teeth per inch; 0.45 mm), and v) M-90 + coarse roll (4 teeth per inch; 0.65 mm). In the sorghum grain experiment, the following sets

Table 1 - Baggers technical specifications

Item	Bagger		
	M-60	M-75	M-90
Bag silo diameter (ft)	6	6	9
Power requirement (hp)	60	75	75
Engagement of the tractor's power take-off (rpm)	540	540	540
Tractor nominal power (hp)	60	75	90

were evaluated: i) M-60 + standard roll (7 teeth per inch; 0.40 mm), ii) M-75 + fine roll (9 teeth per inch; 0.30 mm), iii) M-75 + intermediate roll (6 teeth per inch; 0.45 mm), iv) M-90 + fine roll (9 teeth per inch; 0.30 mm), and v) M-90 + intermediate roll (6 teeth per inch; 0.45 mm).

For both experiments, three bags, representing the experimental units, were prepared for each set. All bags measured 60 m in length. Those produced by the M-60 and M-75 baggers had a diameter of six ft, whereas those from the M-90 bagger had a diameter of nine ft. During the bag-filling process, five bags (one from each treatment) were filled simultaneously to standardize the grains processed by each equipment setup. All baggers were equipped with a water addition (rehydration) system. Thus, immediately after grinding, the grains were rehydrated to reach approximately 65% dry matter and subsequently conveyed into the bag via the machine's auger. After filling, the bags were cored at five points along their length, where samples were collected. Considering the five sets evaluated per crop, a total of 75 samples were obtained per experiment. Each sample was immediately ensiled in 5-L jars, which were then transported to the Department of Animal Science at UFLA and stored in a closed room at ambient temperature for 90 days.

The throughput of each set (tons/hour) was monitored by measuring the number of kilograms ground per minute, which was then used to calculate the equivalent throughput per hour (Tables 2 and 3).

Table 2 - Chemical composition of rehydrated corn grains prior to ensiling and grinding rate of the evaluated equipment sets (n = 3)

Item	Treatment				
	M-60+standard roll	M-75+intermediate roll	M-75+coarse roll	M-90+intermediate roll	M-90+coarse roll
Dry matter (%)	62.5 ± 0.27	62.6 ± 0.16	62.6 ± 0.24	62.7 ± 0.38	62.3 ± 0.27
Ash (% DM)	1.22 ± 0.03	1.20 ± 0.07	1.18 ± 0.12	1.16 ± 0.09	1.19 ± 0.12
Neutral detergent fiber (% DM)	8.48 ± 1.01	8.54 ± 0.94	7.99 ± 0.99	7.85 ± 1.13	7.94 ± 1.09
Acid detergent fiber (% DM)	2.99 ± 0.41	3.01 ± 0.39	2.79 ± 0.60	2.87 ± 0.45	2.63 ± 0.59
Crude protein (% DM)	9.09 ± 0.02	9.11 ± 0.09	9.12 ± 0.18	9.08 ± 0.01	9.08 ± 0.07
Ether extract (% DM)	3.46 ± 0.13	3.53 ± 0.38	3.34 ± 0.14	3.21 ± 0.22	3.33 ± 0.28
Starch (% DM)	72.5 ± 1.21	72.3 ± 1.53	72.4 ± 1.43	72.2 ± 1.40	72.9 ± 0.95
Prolamin (% DM)	5.49 ± 0.44	5.48 ± 0.38	5.65 ± 0.24	5.60 ± 0.38	5.58 ± 0.42
	Grinding rate (ton/h)				
	16.3 ± 4.26	52.7 ± 5.25	51.0 ± 5.69	51.9 ± 3.82	54.9 ± 9.25

Table 3 - Chemical composition of rehydrated sorghum grains prior to ensiling and grinding rate of the evaluated equipment sets (n = 3)

Item	Treatment				
	M-60+standard roll	M-75+fine roll	M-75+intermediate roll	M-90+fine roll	M-90+intermediate roll
Dry matter (%)	63.3 ± 0.15	63.2 ± 0.20	63.5 ± 0.12	63.3 ± 0.26	63.2 ± 0.20
Ash (% DM)	1.73 ± 0.11	1.70 ± 0.13	1.67 ± 0.13	1.70 ± 0.31	1.73 ± 0.18
Neutral detergent fiber (% DM)	9.70 ± 1.56	9.98 ± 2.22	10.0 ± 1.61	9.27 ± 1.45	10.0 ± 1.46
Acid detergent fiber (% DM)	4.28 ± 1.72	4.04 ± 1.55	4.41 ± 1.43	3.99 ± 1.49	4.24 ± 1.46
Crude protein (% DM)	10.3 ± 0.12	10.2 ± 0.10	10.3 ± 0.23	10.3 ± 0.12	10.2 ± 0.06
Ether extract (% DM)	3.37 ± 0.28	3.55 ± 0.09	3.69 ± 0.30	3.36 ± 0.29	3.67 ± 0.13
Starch (% DM)	71.2 ± 0.31	69.2 ± 1.48	71.0 ± 1.27	70.6 ± 1.11	70.0 ± 0.12
Prolamin (% DM)	5.30 ± 0.20	5.20 ± 0.14	5.44 ± 0.17	5.31 ± 0.08	5.45 ± 0.13
	Grinding rate (ton/h)				
	27.2 ± 3.81	43.1 ± 4.25	47.4 ± 7.08	41.1 ± 3.95	45.5 ± 8.09

2.2. Sample preparation, analyses, and calculations

Samples of the raw material (prior to ensiling) and of the silages (from the 5-L jars) were used for analyses. For evaluation of particle size distribution, a 300-g sample was placed in a forced-air circulation laboratory oven at 55 °C for drying. After that process, the particles of the samples were separated by size using an orbital sieve shaker with intermittent tapping (Rotap, MA 750, Marconi, Piracicaba, Brazil). The sieve set consisted of mesh openings of 6.70, 4.75, 3.35, 2.36, 1.70, 1.18, and 0.60 mm, plus a bottom collection tray. Approximately 100 g of the dry sample was shaken for 10 minutes at 100 rpm. The geometric mean diameter (GMD) was determined according to Yu et al. (1998). The number of whole grain kernels was determined through manual counting in a 100-g sample.

The chemical composition, fermentation end products, and microbial counts were determined in duplicate for each subsample. Subsamples of 350 g were pre-dried in a forced-air circulation oven at 55 °C for 72 hours and then ground in a Wiley mill (model TE-680, Philadelphia, USA) equipped with a 1-mm screen. After grinding, the dry matter (DM) content was determined by drying in a laboratory oven at 105 °C (method 934.01; AOAC, 1990). Crude protein (CP) was obtained using the Kjeldahl method and calculated as total N $\times$ 6.25 (method 984.13), and the ash content (AC) was determined by complete combustion in a muffle furnace at 600 °C for 5 h (method 942.05). Ether extract (EE) was quantified using the Soxhlet method (method 963.15) according to the AOAC (1990). To determine the neutral detergent fiber (NDF) concentration, the samples were treated with thermostable amylase sodium sulfite (method F-012/1, Detmann et al., 2021). Acid detergent fiber (ADF) was obtained using method F-014/1 (Detmann et al., 2021). Starch concentration was determined by enzymatic hydrolysis with α -amylase and amyloglucosidase, followed by detection of the released glucose by colorimetry, as described by Fernandes et al. (2022), adapted from Hall (2015). Prolamin was quantified according to Nellis et al. (2013).

For analyses of pH, fermentation profile, and microbiology, additional 200-g samples were collected. Aqueous extracts of the raw material and silage were prepared by mixing 30 g of wet samples and 270 g of deionized water, which were maintained under continuous agitation in a homogenization device (Stomacher 400, Seward, London, UK) for 4 min at 200 rpm. Aliquots were used to measure pH with a potentiometer (model Edge HI 11310; Hanna Instruments, Woonsocket, RI, USA; Bernardes et al., 2019). Other aliquots, of silage samples, were frozen at -20 °C for subsequent analysis of fermentation products. A third group of aliquots, also from silage samples alone, was diluted in peptone physiological saline solution to perform microbiological analyses. The surface plating technique on YGC Agar culture medium (Fluka, Sigma-Aldrich Química Brasil LTDA) was used for yeast and mold counts. Serial dilutions from 10^{-1} to 10^{-4} were prepared in duplicate and incubated at 28 °C for 3 and 5 days, respectively. After incubation, the colonies were counted individually, based on their macromorphological characteristics. For lactic acid bacteria (LAB) counts, the same technique described for yeasts and molds was used. However, MRS Agar culture medium was used (HiMedia, Biosystems Comercial de Importação e Exportação e Equipamentos para Laboratório) and the serial dilutions were from 10^{-2} to 10^{-5} . The plates were incubated at 35 °C for 3 days, and then counting was performed. Microorganism counts were expressed as colony-forming units (CFU) in $\log_{10}$.

The aqueous extract aliquot was thawed and centrifuged at $10,000 \times g$ for 15 min at 4 °C to obtain the supernatant, which was used for quantification of the fermentation end products. The organic acid and alcohol concentrations in the silage were determined using high performance liquid chromatography (HPLC, Shimadzu). The equipment had a quaternary pump (LC-20AT), diode-array detector (DAD, SPD-20A), degasser (DGU-20A5), and interface module (CBM-20A). The samples were automatically injected using an autosampler (SIL-20A). The analytes were separated on a Supelcogel 8H column (300 mm $\times$ 7.8 mm) (code 59246-U) equipped with a Supelcogel 8H guard column (10 mm $\times$ 7.8 mm), using isothermal elution with 0.005 mol/L H_2SO_4 buffer solution as the mobile phase, at a flow rate of 0.5 mL/min and column temperature of 30 °C. The injection volume was 20 μ L. The acids were analyzed at 210 nm, while the sugars and alcohols were determined using a refraction index detector. The compounds were identified by comparing the retention times with known standards and quantified by external calibration. All the samples and patterns were analyzed in duplicate.

2.3. Starch degradation

Ruminal incubation was performed under an experimental protocol reviewed and approved by the Ethics Committee on Animal Use of the Universidade Federal de Lavras (protocol #039/2023). To evaluate *in situ* starch degradability, raw material and silage samples were dried in a forced-air circulation oven at 55 °C for 72 h and then ground in a Wiley mill (Wiley TE-680, Philadelphia, USA) with a 2-mm mesh. Bags (10 × 20 cm, with microporosity of 50 ± 10 µm) were used according to the methodology described by Gusmão et al. (2021). Three rumen-cannulated cows of the Tabapuã breed were used. Their diet consisted of a total mixed feed ration composed of 56.5% corn silage, 11% grain corn, 28.7% dried distiller's grain with solubles, 0.8% urea, and 3.0% minerals (DM basis). The cows underwent a 15-day feed adaptation period. The bags with the samples were placed inside 2 mesh bags (30 × 40 cm) and incubated in the rumen for 7 hours. Blank bags (without samples) were also included in the mesh bags and incubated to correct for possible DM infiltration into the sample bags. Immediately after incubation, the bags were immersed in cold water to halt fermentation. They were then rinsed in a washing machine set to rinse and spin cycles with water at room temperature. Five wash and spin cycles were used to ensure cleaning of the bags. Two control bags (0-h incubation) were washed together with the incubated bags to correct for particle losses. After the washing process, the bags were dried in a forced-air laboratory oven at 55 °C for 48 h, ground using a mortar and pestle to pass through a 1 mm sieve, and analyzed for starch, as previously described.

2.4. Aerobic stability assay

At the time of silo opening, approximately 3 kg of silage sample from each jar was transferred to polystyrene boxes (25 × 17cm) for 120 h at 30.6 ± 1.9 °C in the experiment with corn grain and 30.8 ± 1.7 °C in the experiment with sorghum grain. To prevent silage dehydration and dust contamination, a sheet of aluminum foil was placed over each box (Tabacco et al., 2009). The ambient temperature and silage temperature were recorded every 10 minutes by data loggers (Elitech RC -5+, RS, Brazil), which were operated through the Escort Console Pro software (version 2.12.07). To record ambient temperature, two temperature data loggers were placed in the room at strategic locations. Aerobic stability was defined as the number of hours the silage remained stable before reaching a temperature 2 °C higher than ambient temperature (Ranjit and Kung, 2000). The pH level was determined after homogenization and sampling after 120 h of aerobic exposure. After sampling, an aqueous extract was prepared by mixing 30 g of wet sample with 270 g of deionized water, which was kept under constant agitation in a homogenization device (Stomacher 400, Seward, London, United Kingdom) for 4 min. The pH level was determined using a potentiometer (Edge HI 11310; Hanna Instruments, Woonsocket, RI, USA; Bernardes et al., 2019).

2.5. Statistical analysis

Data distribution was initially assessed using the UNIVARIATE procedure. Variables that did not meet the normality assumption (concentrations of propionic acid and 1,2-propanediol, and pH after aerobic exposure) were transformed using the RANK procedure. The MIXED procedure of SAS software (SAS Institute Inc., Cary, NC, USA) was used, considering equipment set as a fixed effect and bag (experimental unit) nested within treatment as a random effect, as expressed by the following model:

$$Y_{ij} = \mu + T_i + S(T)_j + \varepsilon_{ij},$$

in which Y_{ij} = observed value of the dependent variable; μ = overall mean; T_i = fixed effect of equipment set i ; and $S(T)_j$ = random effect of bag nested within equipment set.

Least squares means were calculated to evaluate differences among treatments, and multiple comparisons were adjusted using Tukey's method, with a significance level set at 5%. The corn and sorghum experiments were analyzed independently.

3. Results

3.1. Particle size distribution, geometric mean diameter, and number of whole grain kernels

The analysis of particle size distribution of processed corn grain showed differences among the treatments across the different sieves (Table 4). The fraction retained on the 4.75 mm sieve was greater in the M-75 with coarse roll treatment (30.5%) and M-90 with coarse roll treatment (30.0%), which differed statistically from the M-60 with standard roll treatment (11.9%; $P = 0.002$). On the 2.36 mm sieve, the M-75 with coarse roll treatment (15.3%) and M-90 with coarse roll treatment (14.0%) showed lower retention than to the M-60 with standard roll treatment (27.5%; $P = 0.004$). On the 1.70 mm ($P = 0.01$) and 1.18 mm ($P = 0.03$) sieves, the M-60 with standard roll treatment showed the highest retention percentages (14.8% and 8.93%, respectively) compared with the other treatments.

The coarsest fraction (6.70 mm) and the number of whole grain kernels (NWK) did not differ statistically ($P \geq 0.05$; Table 4). The absolute number of whole grain kernels per 100 g of sample ranged from 3 to 10, with similar mean values across treatments ($P = 0.95$). In contrast, the GMD of the particles differed among the treatments ($P = 0.01$). The smallest GMD was observed in M-60 with a standard roll ($P = 0.01$; 3.25 mm), while the largest GMD was found in M-90 with an intermediate roll (4.67 mm). The other treatments exhibited intermediate values of GMD (3.84, 4.04, and 4.47 mm).

In the sorghum grain experiment, the particle size distribution also exhibited differences ($P \leq 0.05$) among the treatments on different sieves (Table 5). On the 3.35 mm sieve, the M-90 with intermediate roll treatment showed the highest retention percentage (9.73%), differing from the M-75 with fine roll treatment (1.73%) and M-90 with fine roll treatment (1.87%) ($P = 0.001$). On the 2.36 mm sieve, the M-75 and M-90 with intermediate roll treatments showed the highest percentages of retained particles (53.4 and 56.7%, respectively), higher than the percentages of the other treatments ($P < 0.001$). Similar results were observed on the 1.70 mm and 1.18 mm sieves, where the treatments with finer roll showed higher percentages of smaller particles. The GMD varied among the treatments ($P = 0.003$); it was largest in the M-90 with intermediate roll treatment (2.60 mm) and smallest in the fine roll treatments (1.99 and 2.02 mm for M-75 and M-90, respectively). The other treatments had intermediate values (2.26 mm and 2.47 mm for M-60 with a standard roll and M-75 with an intermediate roll, respectively). The NWK per 100 g of sample was higher in the treatments with intermediate rolls, especially in M-90 (919 grain kernels, equivalent to 24.0%), which differed from the treatments with fine rolls (e.g., M-75 with 178 kernels and 4.18%) ($P = 0.007$).

Table 4 - Particle size distribution, geometric mean diameter (GMD), and number of whole kernels (NWK) in rehydrated corn grain silages as affected by different equipment sets

Item	Treatment					SEM	P-value
	M-60+standard roll	M-75+intermediate roll	M-75+coarse roll	M-90+intermediate roll	M-90+coarse roll		
6.70 mm	3.33	3.07	6.13	4.53	10.0	1.94	0.073
4.75 mm	11.9b	20.9ab	30.5a	24.0a	30.0a	2.39	0.002
3.35 mm	24.0	34.1	37.3	33.3	34.3	4.18	0.360
2.36 mm	27.5a	24.8a	15.3b	22.3ab	14.0b	2.01	0.004
1.70 mm	14.8a	7.60ab	5.07b	6.67b	4.00b	1.60	0.014
1.18 mm	8.93a	4.67ab	3.40b	4.53ab	4.00b	1.05	0.027
0.6 mm	5.60	2.67	1.40	2.80	2.53	1.41	0.500
Bottom	4.00	2.13	1.07	1.87	1.20	1.35	0.674
GMD (mm)	3.25b	3.84ab	4.47ab	4.04ab	4.67a	0.27	0.010
NWK ¹	8.00	3.00	3.00	3.00	10.0	5.38	0.948
NWK (%) ²	3.27	3.53	7.10	5.87	9.60	2.41	0.171

¹ Number of whole kernels per 100 g of sample.

² % of whole kernels in 100 g of sample.

Means followed by different letters in the row differ significantly according to Tukey's test ($P < 0.05$).

Table 5 - Particle size distribution, geometric mean diameter (GMD), and number of whole kernels (NWK) in rehydrated sorghum grain silages as affected by different equipment sets

Item	Treatment					SEM	P-value
	M-60+standard roll	M-75+fine roll	M-75+intermediate roll	M-90+fine roll	M-90+intermediate roll		
3.35 mm	4.13ab	1.73b	6.96ab	1.87b	9.73a	1.06	0.001
2.36 mm	41.3b	25.6c	53.4a	28.8c	56.7a	3.07	<0.001
1.70 mm	33.9ab	40.7a	24.8ab	38.0ab	22.0b	3.58	0.019
1.18 mm	11.6b	20.0a	8.96b	18.9ab	7.33b	1.76	<0.001
0.6 mm	5.60	8.27	3.74	8.40	3.47	1.57	0.144
Bottom	3.47	3.73	2.14	4.00	0.80	1.99	0.717
GMD (mm)	2.26bc	1.99c	2.47ab	2.02c	2.60a	0.07	0.003
NWK ¹	562ab	178b	867a	338b	919a	123	0.015
NWK (%) ²	14.7ab	4.18b	21.6a	8.1b	24.0a	2.87	0.007

¹ Number of whole kernels per 100 g of sample.² % of whole kernels in 100 g of sample.

Means followed by different letters in the row differ significantly according to Tukey's test (P<0.05).

3.2. Chemical composition and starch degradability

The analysis of the chemical composition of the silages showed no differences ($P \geq 0.05$) for the concentrations of dry matter (DM), ash, neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP), ether extract (EE), starch content, or prolamin, in either the experiment with corn grain or in that with sorghum grain (Tables 6 and 7). Regarding starch degradability, no differences were observed among the treatments in the experiment with sorghum ($P = 0.42$). However, in the experiment with corn, the M-60 with standard roll combination exhibited the highest degradability (72.6%), while the lowest value was observed with M-75 with coarse roll (64.3%; $P = 0.02$).

Table 6 - Chemical composition and starch degradability in rehydrated corn grain silages as affected by different equipment sets

Item	Treatment					SEM	P-value
	M-60+standard roll	M-75+intermediate roll	M-75+coarse roll	M-90+intermediate roll	M-90+coarse roll		
Dry matter (%)	61.8	62.0	61.6	62.0	61.7	0.46	0.978
Ash (% DM)	1.22	1.25	1.19	1.22	1.23	0.04	0.858
Neutral detergent fiber (% DM)	7.63	8.08	8.00	7.63	7.73	0.60	0.943
Acid detergent fiber (% DM)	2.66	2.95	2.73	2.86	2.63	0.23	0.883
Crude protein (% DM)	9.22	9.40	9.32	9.37	9.52	0.18	0.866
Ether extract (% DM)	3.41	3.49	3.45	3.41	3.43	0.13	0.977
Starch (% DM)	71.9	72.2	71.8	71.9	72.0	0.89	0.980
isSD (% starch) ¹	72.6a	68.0ab	64.3b	71.7ab	65.9ab	1.67	0.023
Prolamin (% DM)	4.85	4.64	4.80	4.70	4.77	0.07	0.171

¹ isSD = ruminal *in situ* starch degradation at 7 h.

Means followed by different letters in the row differ significantly according to Tukey's test (P<0.05).

Table 7 - Chemical composition and starch degradability in rehydrated sorghum grain silages as affected by different equipment sets

Item	Treatment					SEM	P-value
	M-60+standard roll	M-75+fine roll	M-75+intermediate roll	M-90+fine roll	M-90+intermediate roll		
Dry matter (%)	62.5	61.7	62.7	62.9	62.0	0.41	0.291
Ash (% DM)	1.72	1.84	1.70	1.66	1.72	0.08	0.625
Neutral detergent fiber (% DM)	9.60	9.64	10.1	9.12	9.91	1.17	0.930
Acid detergent fiber (% DM)	4.17	4.25	4.23	3.90	4.18	0.72	0.981
Crude protein (% DM)	9.81	9.81	9.85	9.83	9.78	0.22	0.999
Ether extract (% DM)	3.72	3.61	3.59	3.62	3.67	0.09	0.722
Starch (% DM)	70.5	70.6	70.4	70.6	70.7	0.53	0.995
isSD (% starch) ¹	52.1	57.0	45.7	53.0	45.5	4.86	0.415
Prolamin (% DM)	4.84	4.89	4.72	4.70	4.77	0.07	0.406

¹ isSD = ruminal *in situ* starch degradation at 7 h.

3.3. pH, microbial counts, and fermentation products

Analysis of the fermentation and microbiological parameters showed no differences among the treatments ($P \geq 0.05$) in either of the experiments (Tables 8 and 9). In the corn experiment, the pH ranged from 3.89 to 3.97. The LAB counts showed values from 4.29 to 4.48 log₁₀ CFU/g, while the yeast and mold populations ranged from 1.11 to 1.68 and from 0.83 to 1.57 log₁₀ CFU/g, respectively.

Table 8 - Fermentation end products and microbial counts in rehydrated corn grain silages as affected by different equipment sets

Item	Treatment					SEM	P-value
	M-60+standard roll	M-75+intermediate roll	M-75+coarse roll	M-90+intermediate roll	M-90+coarse roll		
pH	3.97	3.94	3.90	3.97	3.89	0.07	0.876
LAB (log CFU/g)	4.29	4.33	4.46	4.48	4.39	0.37	0.978
Yeasts (log CFU/g)	1.50	1.68	1.44	1.66	1.11	0.39	0.811
Molds (log CFU/g)	0.83	0.90	1.36	1.57	1.29	0.31	0.528
Lactic acid (% DM)	3.43	3.47	3.69	3.60	3.61	0.17	0.796
Acetic acid (% DM)	0.63	0.80	0.92	1.02	0.99	0.21	0.694
Propionic acid (% DM)	0.09	0.10	0.13	0.08	0.07	0.02	0.527
1,2-propanediol (% DM)	0.02	0.05	0.03	0.04	0.04	0.01	0.761

Table 9 - Fermentation end products and microbial counts in rehydrated sorghum grain silages as affected by different equipment sets

Item	Treatment					SEM	P-value
	M-60+standard roll	M-75+fine roll	M-75+intermediate roll	M-90+fine roll	M-90+intermediate roll		
pH	4.00	3.92	4.05	3.93	3.90	0.08	0.564
LAB (log CFU/g)	4.98	4.82	5.05	4.93	4.96	0.19	0.936
Yeasts (log CFU/g)	1.68	1.54	1.47	1.22	0.92	0.66	0.938
Molds (log CFU/g)	1.56	1.62	1.58	1.73	1.67	0.19	0.971
Lactic acid (% DM)	3.78	3.73	3.87	3.97	4.02	0.46	0.986
Acetic acid (% DM)	0.68	0.67	0.66	0.72	0.74	0.12	0.949
Propionic acid (% DM)	0.06	0.11	0.09	0.07	0.06	0.04	0.633
1,2-propanediol (% DM)	0.08	0.02	0.07	0.05	0.04	0.03	0.439

Fermentation product concentrations were as follows: acetic acid from 0.63 to 1.02%, propionic acid from 0.07 to 0.13%, and 1,2-propanediol from 0.02 to 0.05%. In the sorghum experiment, the pH oscillated from 3.90 to 4.05. The LAB counts ranged from 4.82 to 5.05 log₁₀ CFU/g, yeasts from 0.92 to 1.68 log₁₀ CFU/g, and molds from 1.56 to 1.73 log₁₀ CFU/g. The concentrations of acetic acid, propionic acid, and 1,2 propanediol ranged from 0.66 to 0.74%, 0.06 to 0.11%, and 0.02 to 0.08%, respectively.

3.4. Aerobic stability test

No effect of the treatments was found for the aerobic stability test in either the corn experiment ($P = 0.69$; Table 10) or the sorghum experiment ($P = 0.38$; Table 10). The silages remained stable for 61.37 to 68.63 hours and for 77.37 to 106.2 hours for corn and sorghum, respectively. Likewise, no differences were observed in pH after 5 d of aerobic exposure in either of the experiments. In corn, values ranged from 4.19 to 5.63 ($P = 0.31$), whereas in sorghum, the variation was from 4.00 to 5.18 ($P = 0.14$).

Table 10 - Aerobic stability (AS; h) in rehydrated corn and sorghum grain silages as affected by different equipment sets

Item	Corn trial					SEM	P-value
	M-60+standard roll	M-75+intermediate roll	M-75+coarse roll	M-90+intermediate roll	M-90+coarse roll		
AS	63.8	61.4	64.9	68.1	68.6	4.42	0.689
pH ¹	5.63	4.61	4.63	4.80	4.19	0.60	0.313
	Sorghum trial						
	M-60+standard roll	M-75+fine roll	M-75+intermediate roll	M-90+fine roll	M-90+intermediate roll		
AS	83.7	77.4	93.3	87.4	106.2	11.4	0.375
pH ¹	4.87	5.18	4.73	4.76	4.00	0.40	0.136

¹ pH after aerobic exposure.

4. Discussion

The use of roller mills has gained prominence because they enable a higher grinding rate (tons/hour) compared to hammermills. Roller mills reduce processing time (Koch, 1996) and even improve particle uniformity (Koch, 1996; Rémond et al., 2004). This greater operational efficiency of bagging machines equipped with roller mills has led producers to opt for reconstituting and ensiling grains after roller processing with the aim of reducing labor costs, time, and energy (Gomes et al., 2020). In addition, processing methods that reduce grain kernel size have often been used to increase starch degradability and the feed efficiency of the animals that consume these silages (Owens et al., 1997; Matsushima, 2006; Owens and Basalan, 2013; Jacovaci et al., 2021). However, the effects of milling associated with conservation of rehydrated grain through use of new processing combinations have not been widely examined in the literature, especially in regard to their effect on physical and chemical composition, fermentation profile, and starch degradability.

Roller processing of grain increases starch degradability, although this effect has been inconsistent across studies (Johnson et al., 2003; Cooke and Bernard, 2005). The variability in these responses may be related to differences in the extent of grain fragmentation and the processing method used (Ferreira and Mertens, 2005; Svihus et al., 2005). In this study, the combination between machinery and roll types affected starch degradability in the corn silages, although this parameter was not affected in the sorghum silages. It is important to emphasize that the method adopted to assess starch degradability in this study may have affected the final results for this variable, since the samples were ground prior to incubation. Despite similar starch content among the treatments, greater degradability was observed in the M-60 standard roll combination, which showed a higher proportion of fine particles, as evidenced

by the lower retention on the 4.75 mm sieve and higher proportions on the 2.36 mm, 1.70 mm, and 1.18 mm sieves. This treatment also exhibited the smallest GMD, confirming the association between grinding intensity and starch availability. These findings are consistent with the results of Lykos and Varga (1995) and Ferraretto et al. (2013), who reported that increased grain fragmentation favors exposure of the starch to digestive enzymes, particularly in corn grain. The absence of an effect in the sorghum grain experiment may be associated with its denser and more compact structure (Rooney and Pflugfelder, 1986; Silva et al., 2020), which reduces grinding efficiency due to greater resistance of the pericarp and endosperm. Among cereal grains, sorghum frequently exhibits lower starch digestibility, which can mainly be attributed to the resistance of the hard peripheral endosperm layer to the action of enzymes (Duodu et al., 2003; Mudge et al., 2017).

Coarse rolls traditionally used for corn and intermediate-roll models used for sorghum, represent older and less precise technologies. In more modern models, the higher number of teeth per inch leads to greater and more uniform fracturing/crushing of grain kernels. When combined with machines adjusted for more intense grinding, these high precision rolls tend to provide substantial gains in starch degradability of rehydrated corn grain, highlighting their potential as a key technology for optimizing the energy resources of these silages. However, for cereal grains such as sorghum, the structural resistance of the grain is still a limiting factor, even in the face of technologies designed to improve processing efficiency.

The particle size distribution data from the experiment with sorghum grain indicate important variations in the degree of grinding provided by the different combinations of machines and rolls. The treatments that used M-75 and M-90 baggers and with intermediate rolls had higher proportions of particles retained on the 2.36 mm sieve and also higher percentages of whole grain kernels. This suggests less efficient processing in terms of grain grinding, which can have a negative impact on exposure of the starch to enzyme attack, although no statistical difference in starch degradability was observed in this study. In contrast, the M-75 treatment with a fine roll led to greater fragmentation, as shown by the higher proportion of particles retained on the smaller sieves, a smaller number of whole grain kernels, and a smaller GMD. This more intense grinding profile is consistent with the expectation of a larger contact surface, even though this condition did not result in greater starch degradability. It is important to note that the NWK, for example, can be used as an indicator of processing efficiency, and high values may be associated with potential losses of *in vivo* digestibility. In this context, the absence of response may be related to the structural resistance of the sorghum endosperm or to the incubation time adopted. This highlights the need for further studies associating particle size, physical processing, and biological responses.

The similarity in chemical composition observed among the treatments in both experiments suggests that physical processing of the grain did not substantially affect the nutritional components of the silages. This uniformity can be attributed to the fact that grinding mainly affects starch availability (Ramos et al., 2009; Miorin et al., 2018) and not necessarily the total concentration of the nutrients analyzed. In addition, the homogeneous fermentation observed across the treatments likely contributed to preservation of the nutrients. These findings indicate that under good ensiling conditions, the chemical composition of the rehydrated sorghum or corn grain silages tends to be more affected by the intrinsic characteristics of the ensiled material than by variations in physical processing of the grain.

The degree of grain processing is often reported as a factor that can affect the fermentation profile of silages, although the literature presents inconsistent results regarding this relationship (Gomes et al., 2020; Saylor et al., 2020; Gervásio et al., 2023). Finer grinding tends to facilitate faster bacterial activity to begin the fermentation process in the silo (Blasel et al., 2006). However, the different processing methods in the experiments and the different GMD of the grain in the sorghum grain experiment were not able to modify the fermentation profile in the present study. It should be noted that unlike hammermills, roller mills predominantly crack the grain by compression, resulting in fewer extremely fine particles (Rémond et al., 2004). This type of milling tends to preserve part of the grain structure, which may limit immediate release of fermentable substrates at the time of ensiling. Furthermore, in the case of sorghum, the lower solubility of its protein matrix (Duodu et al., 2003) may have contributed

to reduced availability of substrates, minimizing the impact of processing on the fermentation parameters. Therefore, even though the GMD varied among the treatments, fermentation followed a similar pattern, possibly due to the combined effects of grain characteristics, type of milling, and initial moisture content of the materials.

Silage fermentation is initiated by epiphytic microorganisms, which act on the available substrates and shape the anaerobic environment, resulting in production of acids and a decline in pH (McDonald et al., 1991). Once this environment has been established, characteristics such as pH and short chain fatty acid concentrations come to regulate which microorganisms remain active or are inhibited (Pahlow et al., 2003; Kung et al., 2018). Thus, even given physical differences, such as particle size distribution among the treatments, the consistent fermentation profile observed in this study indicates that the environment within the silo had uniform characteristics. This scenario may explain the similarity in microbial counts across the treatments. In addition, specific factors of the ensiling process in this study, such as the initial moisture content of the materials, an adequate compaction and sealing process, and the low final pH achieved, contributed to creating a stable environment inhospitable to the growth of spoilage microorganisms (Kung et al., 2018), sustaining a microbiological pattern across the treatments.

The aerobic stability of the silages likewise did not exhibit variations among the treatments in either of the experiments. As described by Pitt (1990) and Wilkinson and Davies (2013), this parameter is affected by a complex interaction of factors, such as ambient temperature, pH, moisture, compaction, population of aerobic microorganisms, and organic acid concentration. In the present study, these variables were similar across the treatments, which may explain the uniformity observed in aerobic stability. In this regard, the absence of differences among the treatments suggests that the degree of grinding, resulting from different combinations between machines and rolls, did not have a relevant effect on this parameter. Similar results were reported by Gervásio et al. (2023), reinforcing the hypothesis that the degree of grinding alone has a limited effect on aerobic stability in grain silages.

The results of this study highlight that the type of grain plays a decisive role in the response to physical processing, as the efficacy of the processing is affected by characteristics intrinsic to each grain, especially the structure of the endosperm and the way the starch is encapsulated within the protein matrix (Zinn et al., 2002).

These findings reinforce that processing strategies should be adapted to the structural characteristics of each grain, aiming to simultaneously maximize efficiency in utilizing nutrients and silage preservation. Furthermore, it is important to consider that, in practice, the choice of the type of machinery and the set of rolls used on farms also involves operational factors (Macken et al., 2006; Piran Filho et al., 2024). The grinding rate (tons/hour) is a decisive parameter for many producers, especially during the harvest period, when the time available for processing and ensiling grains is limited. Machines with higher grinding capacity increase process efficiency by enabling better use of available labor and reducing total operation time. These are strategic aspects, above all on farms with large scale production. Thus, the results observed in this study provide practical information for decision making in the field, highlighting that the choice of the processing system should consider not only the animal science response, but also the operational feasibility of the production system.

5. Conclusions

The combinations of bagging machines and roll types evaluated did not affect the chemical composition, fermentation profile, microbial counts, or aerobic stability of rehydrated corn and sorghum grain silages. However, in corn, the combination of the M-60 bagger with the standard roll resulted in the highest starch degradability and the most intense particle fragmentation. In sorghum, the fine rolls used with the M-75 and M-90 baggers decreased the number and proportion of whole kernels and reduced the GMD, indicating greater fragmentation, although starch degradability remained unaffected. Therefore, the use of the M-60 bagger with the standard roll is recommended for corn to optimize starch degradability, despite the fact that the M-60 has a lower grinding rate compared to the other baggers. If the grinding rate becomes a limiting factor in the field, the use of intermediate rolls installed

on M-75 and M-90 baggers is advisable. For sorghum, the use of fine rolls mounted on the M-75 and M-90 baggers is recommended to improve grain fragmentation.

Data availability

All data are available within the manuscript.

Author contributions

Conceptualization: Melo, N. N.; Cordeiro, M. W. S. and Bernardes, T. F. **Data curation:** Melo, N. N.; Cordeiro, M. W. S. and Bernardes, T. F. **Formal analysis:** Melo, N. N.; Cordeiro, M. W. S. and Bernardes, T. F. **Funding acquisition:** Bernardes, T. F. **Investigation:** Melo, N. N.; Cordeiro, M. W. S. and Bernardes, T. F. **Methodology:** Melo, N. N. and Bernardes, T. F. **Project administration:** Bernardes, T. F. **Supervision:** Bernardes, T. F. **Validation:** Melo, N. N.; Cordeiro, M. W. S. and Bernardes, T. F. **Visualization:** Melo, N. N.; Cordeiro, M. W. S. and Bernardes, T. F. **Writing – original draft:** Melo, N. N.; Cordeiro, M. W. S. and Bernardes, T. F. **Writing – review & editing:** Melo, N. N.; Cordeiro, M. W. S. and Bernardes, T. F.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

We thank Marcher (Gravataí, RS, Brazil) for sponsoring this study.

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