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Quality of sorghum hybrid silages at different storage times

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Abstract

The objective of this study was to evaluate the nutritional changes in silages of four sorghum hybrids at different storage times. The design was a completely randomized in a 4 × 9 arrangement of plots with four replications. The four sorghum hybrids, Qualysilo, Chopper, Dominator, and Maxisilo, were allocated to the plots. In the subplots, sampling times were considered in fresh material and after 1, 3, 7, 14, 28, 56, 112, and 224 days of storage. The material was ensiled in experimental polyvinyl chloride silos and subsequently evaluated for chemical composition and fermentative profile over the nine different periods of the fermentation process. Crude protein was reduced by 1.21g/kg per day until the third day of fermentation. The levels of neutral detergent insoluble nitrogen and acid detergent insoluble nitrogen exceeded the upper limit of 311 g/kg of N. Of the studied silages, an NDF content of 734 g/kg was obtained in Maxisilo, which was higher than the other silages (average: 547 g/kg). Silage production can be achieved with the four materials; however, the Maxisilo sorghum provides silages of lower quality, with a DM content of less than 30%. The other materials fit into the nutritional profiles proposed by the literature, characterizing them as good quality silages.

Keywords: anaerobiosis, feed preservation, nutritional value, ruminants
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Introduction

Livestock production has an impact on the global economy, being essential for the economic survival of several regions around the world. In the Pampa Biome in Brazil, Argentina, and Uruguay, livestock production is the main economic activity, with cattle and sheep being the dominant species (Marchi *et al.,* 2018). However, due to subtropical and temperate climates with four, well-characterized seasons (Roesch *et al.,* 2009) and extremely sandy texture and fragility of soil, the natural grasslands have seasonal forage production and quality (Rubert *et al.,* 2018).

To balance the forage seasonality caused by droughts and low temperatures, and to ensure the sustainability of livestock production in the Pampa region, forage planning must be adopted (Malaguez *et al.,* 2017). The production of silages is one of the options in a forage planning system, and for less fertile soils, the sorghum plant is the most suitable.

Silage making is a method of feed preservation in anaerobic conditions, whereby biochemical processes in ensiled forage ensure a reduction in pH and preservation of nutritional value. However, this can be altered by failures in the ensiling process or by the fermentative dynamics during silage storage. The chemical composition of silages can be changed depending on the region of production (Bernardes *et al.,* 2018). Information on silage sorghum fodder obtained in the Pampa region is scarce, as is analyses of the nutritional content over time. Thus, the objective was to study was to study the nutritional changes in the silage of four sorghum hybrids after different storage times.

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Material and Methods

The work was conducted at the Federal University of Pampa Experimental farm and Animal Nutrition Laboratory of Unipampa - Uruguaiana *Campus*, located at the Rio Grande do Sul, Brazil (29°45'17" S; 57°05'18" W; 66 m above sea level).

The design was completely randomized plots; subdivided in a 4 × 9 arrangement, with four replications. The plots were allocated to four sorghum hybrids, Qualysilo, Chopper, Dominator, and Maxisilo. In the subplots, sampling times were considered in fresh material (time zero) and after 1, 3, 7, 14, 28, 56, 112, and 224 days of storage.

Cultures were implanted using a continuous flow seeder system with a spacing of 0.34 m. At the time of sowing, the seeds were treated with CRUISER® (thiamethoxam) insecticide. A base fertilizer of 120 kg/ha of formulated 8:20:15 (N:P:K) was used. A cover fertilizer of 50 kg/ha of nitrogen was applied as urea 45 d after sowing.

The harvest was carried out when it was identified that the panicle of the plants presented grains with 70% pasty consistency and 30% milky consistency, obtaining a forage mass with an ideal dry matter content for silage of ~35%. With the aid of a tractor, the green material was cut 15 cm from the ground and the equipment knives were adjusted for particle chopping of 2–5 cm.

The harvested material was stored in experimental silos of polyvinyl chloride (PVC), equipped with a Bunsen-type valve to allow gases to escape during fermentation. At the bottom, 0.5 kg of clean sand was used for the purpose of draining the effluents during storage. For adequate compaction, a density of 600 kg/m^3 was used.

At the time of the opening of the silos, hydrogen potential (pH) of silages was measured according to the method of Cherney & Cherney (2003). Ammonia nitrogen (NH_3-N) was determined according to the method of Bolsen *et al*. (1992).

Samples pre-dried in a forced air oven at 55 °C for 72 h were ground in a Willey (STAR FT 60, FORTINOX, São Paulo, Brazil) mill with a 1-mm sieve. The contents of dry matter (DM - method 950.15, AOAC, 2000), mineral matter (MM - method 942.05, AOAC, 2000), ether extract (EE - method 920.39, AOAC, 2000), crude protein (CP - method Kjeldahl 984.13, AOAC, 2000), and lignin (method 973.18, AOAC, 2000) were determined according to the respective methods.

The organic matter (OM) content was calculated according to the formula:

$$\text{OM (\%)} = 100 - \text{MM} \tag{1}$$

The concentrations of neutral detergent fibre (NDF) and acid detergent fibre (ADF) were determined according to the method of Van Soest *et al*. (1991). The hemicellulose (HEM) content was calculated as the difference between NDF and ADF. Neutral detergent insoluble nitrogen (NDIN) and acid detergent insoluble nitrogen (ADIN) levels were determined according to the method of Licitra *et al*. (1996).

Concentrations of total carbohydrates (TC) and non-fibre carbohydrates (NFC) were obtained using the formulae (Sniffen *et al*. (1992):

$$\text{TC} = 100 - (\%\text{CP} + \%\text{EE} + \%\text{MM}) \tag{2}$$

$$\text{NFC} = 100 - (\%\text{NDF} + \%\text{CP} + \%\text{EE} + \%\text{MM}) \tag{3}$$

Total digestible nutrients (TDN) were calculated according to the method of Bolsen (1996) and dry matter consumption as a percentage of live weight (DMCLW) was calculated by estimate, according to the method of Mertens (1997). Digestible dry matter (DIGDM) was determined according to the method of Rohweder *et al*. (1978).

For statistical analysis of the data, the SISVAR statistical program was used. The data were submitted to variability analysis and, when the significance was established, the parameters were compared using Tukey's test (5%). All silage storage times were compared using regression analysis. Linear and quadratic models were tested, and the coefficients of the equations for each model were tested at the 5% level of significance using Student's *t*-test. To choose the regression model that best explained the behaviour of the data, the determination coefficient (R^2) was considered in addition to the significance. Only the equations of the contents that obtained $R^2 \geq 0.6$ were discussed; the equation generated by the analysis explained 60% of the variation in the content in relation to time, whereas 40% of the variation was random.

Results and Discussion

There was an effect of the interaction of factors on the variables studied, except for CP, FC, NDF, TDN and DMCLW, which were affected only by the isolated factors (Table 1).

The dry matter contents did not fit the tested regression models, and in all silage times, the lowest DM content was observed in the silages obtained with Maxisilo (Table 3). As forage silage with a low

DM content causes quality losses (Borreani *et al.,* 2018) and promotes the development of *Clostridium* (Driehuis *et al.,* 2018), this material must be carefully monitored in respect of the DM content of the silage. For obtaining quality silages, the indicated DM required is ~30% (McDonald *et al.,* 1991) for a rapid reduction of pH due to the action of lactic acid bacteria (Muck *et al.,* 2018) and the inhibition of the development of undesirable microorganisms (Driehuis *et al.,* 2018).

Qualysilo, Chopper, and Dominator silages increased NH_3-N up to 153, 50, and 168 days, respectively, with subsequent reduction, whereas in Maxisilo, NH_3-N increased 0.0237% of total N every day of the fermentation period (Table 2). NH_3-N is the result of the plant and microbial proteolysis that occurs inside the silo and is higher in humid silages due to the action of microorganisms of the genus, *Clostridium* (Kung *et al.,* 2018).

Proteolysis starts right after cutting the forage and extends during ensiling until the time when acidic conditions are established inside the silo (Woolford, 1984). The NH_3-N production in silos occurs through biochemical means called deamination, decarboxylation, oxidation, and reduction (Pires *et al.,* 2013), and, together with other non-nitrogen compounds, they interfere with ruminal metabolism and the regulation of consumption in ruminants (Grant & Ferraretto, 2018). Although increases in NH_3-N were observed in all silages, quality was preserved, because no silage time produced NH_3-N higher than the threshold values of 10 to 15% of total N (Kung *et al.,* 2018).

Rapid pH reduction was observed in all hybrids (Table 2), indicating adequate preservation of silages (Van Soest, 1994). On the third day of fermentation, Chopper, Dominator, and Maxisilo silages had a pH of <4.2; the range indicated for well-preserved silages extends to 3.6 (Moura *et al.,* 2016). Although the Qualysilo silage took 6 d to reduce the pH, it was also fast (Table 2). Together with NH_3-N, pH is a safe indicator of the fermentative quality of silages, since low values of both indicate a rapid stabilization of ensiled material (Moura *et al.,* 2016).

Mineral matter was higher in silages obtained using hybrid, Maxisilo, after 14 d of fermentation, with the opposite result for OM (Table 3), indicating a lower nutritional value for this silage. Since feed OM contains nutrients that are potential energy providers such as carbohydrates, lipids, and proteins, its reduction can also reduce the energy potential of foods (Malaguez *et al.,* 2017). Not a nutritionally significant source of minerals, MM contains a large amount of silica, which is responsible for the thickening of the cell wall together with lignin (Ruppenthal *et al.,* 2016). In fodder, this mineral is characterized as a potent reducer of the digestibility of the constituents of the cell wall, with a consequent reduction in DM consumption, since its solubility in the rumen environment inhibits the action of cellulolytic ruminal microorganisms (Van Soest & Jones, 1968). Similarly, increasing the amount of silica in its dry mass increases the ash content (Tolentino *et al.,* 2016).

The silage CP was markedly altered by the silage storage time only until the third day of fermentation, with a reduction of 1.21 g/kg per day ($\hat{y} = -1.2106x + 64.204$; $R^2 = 0.99$). After this period, CP changes were not statistically significant, indicating that proteolysis, the process responsible for these reductions, occurred more intensely in the first days of the fermentation process. Differences were observed between the studied hybrids. The silage obtained with Maxisilo had a lower CP content (51.33 g/kg) than the others. Silage with a CP content of 57.49, 60.51, and 67.74 g/kg, respectively, were obtained from the hybrids, Qualysilo, Chopper, and Dominator, which was lower than that of Stella *et al.* (2016), who determined a CP content of 73 g / kg in sorghum silages.

For adequate performance, ruminants depend on a balanced supply of nutrients (Martineau *et al.,* 2011), of which nitrogen is the most critical (Hristov *et al.,* 2019). Nitrogen compounds are a source of amino acids, are incorporated in nucleic acids and are essential for the synthesis of microbial protein (Schuba *et al.,* 2017). However, not all nitrogenous fractions that make up the CP of foods are used by ruminants, so their separate study becomes relevant to estimate the nutritional value of feeds (Martineau *et al.,* 2011).

The content of NDIN and ADIN of the studied silages (Table 2) requires attention because they exceeded the upper limit of 311 g/kg of total N for conserved fodder (Machacek & Kononoff, 2009). These parameters indicate the nitrogen fractions linked to the plant cell wall and insoluble in neutral and acid detergent, respectively. As they are expressed in relation to total nitrogen, the higher the values, the lower the availability of nitrogen for use by animals, especially in the case of ADIN. Although ADIN can be partially digestible (Machacek & Kononoff, 2009), this fraction is accepted as the nitrogen that is nutritionally unavailable to ruminants (Sniffen *et al.,* 1992) and it is negatively correlated with the digestibility of N in the diet (Van Soest, 1994). These values can be influenced by the physiological maturity stage of the plant during harvest and its lignification (Moura *et al.,* 2016) and heat damage (Machacek & Kononoff, 2009) during prolonged exposure to temperatures above 45–50 °C (Kung *et al.,* 2018). This condition favours the occurrence of the Maillard reaction (Gayer *et al.,* 2019), which is the non-enzymatic chemical polymerization of soluble sugars and hemicellulose with amino acids of food (McDonald *et al.,* 2010).

The content of EE was higher in Chopper silage in practically all fermentation times (Table 2) due to the greater participation of grains in the ensiled mass of this hybrid. In the study of TC, no statistically significant differences were observed, with an average value of 846.21 g/kg. The NFC content was higher in the Maxisilo silage, whereas the highest concentration of NFC from the seventh day of fermentation was observed in the Chopper silage (Table 3). As NFC are rapidly fermentable in the rumen, they provided a higher energy content in the Chopper silage (TDN: 596 g/kg) compared to the other hybrids (Qualysilo: 519 g/kg; Maxisilo: 503 g/kg, and Dominator: 517 g/kg). These, since they are synchronized with the availability of nitrogenous compounds, are the most efficient in increasing the production of milk and meat as they are substrates for the synthesis of microbial protein. For this reason, its maintenance throughout the silage storage period, as observed in this study (Table 2) and also by Hristov *et al.* (2019) in corn silages, is desirable.

As NDF is directly related to the consumption of DM (Hristov *et al.,* 2019), these parameters must be studied together. When studying the cell wall components of the silages, it was found that the NDF did not change over the storage period, in agreement with the results of Hristov *et al.* (2019), who studied long-term corn silage storage. Of the studied silages, Maxisilo had a higher NDF content (734 g/kg) than the others (average: 547 g/kg). For DM consumption expressed in relation to percentage of live weight, the Chopper hybrid silage could be added in greater quantity to the diets, reaching up to 2.08% of live weight. With a lower inclusion limit and requiring greater caution in its use in diets, especially in high production animals, Maxisilo silage was obtained with its inclusion limited to 1.74% of live weight. For both silages of the Qualysilo and Dominator hybrids, the consumption potential obtained was intermediate and identical at 1.89% of live weight.

NDF is the main source of energy in ruminants (Krämer-Schmid *et al.,* 2016), and together with CP, reflects the nutritional value of bulky feed (Zhang *et al.,* 2018). Thus, as an NDF content in the diet above 485 g/kg and 353 g/kg limits consumption and performance of dairy cows and beef cattle in feedlots, respectively (Arelovich *et al.,* 2008), due to the rumen-filling effect (Krämer-Schmid *et al.,* 2016), the limits of inclusion of these silages in diets should be considered.

In agreement with the results obtained with the NFC, the ADF was lower in the silages of the Chopper hybrid, whose result was mainly influenced by the content of lignin, a component of the ADF, also lower in the silages of this hybrid (Table 2). The NDF content does not affect the digestibility of the ADF, however, the reverse occurs (Kendall *et al.,* 2009). For this reason, it is essential to know the ADF content of bulky feed for ruminants. The ADF is used as a predictor of digestibility due to the presence of lignin (Machacek & Kononoff, 2009). Agreeing with results observed by Hristov *et al.* (2019) in corn silages, this fraction increased in all silages over the storage period (Table 2). The increase is due to the concentration of lignin in the ensiled mass resulting from the consumption of carbohydrates in the fermentation phase of the silages.

High levels of lignin in silages are not desirable because it is practically indigestible and chemically phenolic; it causes a physical and chemical barrier to fibrolytic microorganisms, compromising the digestibility of the fibrous fractions of the diet. Although NDF is the most widely-used consumption predictor, feed with a high ADF also has potential for consumption depression due to the filling effect (Poczynek *et al.,* 2020). Thus, the higher the lignin content, the greater the filling effect (Poczynek *et al.,* 2020) and the lower the digestibility of the diet (Marcos *et al.,* 2018), both accentuated by cellulose content (Table 2).

Table 2 also indicated an increase over the course of the fermentative period due to the consumption of soluble carbohydrates and an increase in the concentration of these constituents in DM. In bulky foods, the higher the content, the lower the nutritive value (Gayer *et al.,* 2019). However, they must always be evaluated together, because even at high concentrations, in forages with low levels of lignin, the ruminal hydrolysis of cellulose and hemicellulose is not impaired and they release polysaccharides, increasing ruminal degradability (Zhao *et al.,* 2018).

Table 1. Analysis of variance showing mean squares and sources of variation in the characteristics of the silages obtained from four sorghum materials at different fermentation times

Parameter	Block	Times (T)	Residue 1	Materials (M)	T*M	Residue 2	CV1	CV2
DF	3	8	24	3	24	81		
DM	390.79*	990.33**	355.6	3550.77*	555.82	279.59	6.29	5.58
NH_3-N	0.06**	39.67**	0.06	13.91**	4.96	0.13	7.16	9.39
pH	0.02**	4.77**	0.01	2.03**	0.16	0.02	2.79	3.65
MM	101.80^{ns}	50.51**	37.86	2280.43**	99.33	41.27	9.24	9.65
OM	101.80^{ns}	50.51**	37.86	2280.43**	99.33	41.27	0.66	0.69
CP	26.47**	414.40**	29.02	1168.56^{ns}	41.58	29.4	9.13	9.19
NDIN	6783.54**	36878.35**	7342.73	176985.70*	7242.65	3987.42	29.83	21.98
ADIN	892.01**	29109.10**	1641.66	245014.13**	7224.32	2115.71	13.02	14.78
EE	8.18**	88.70**	4.65	485.71**	45.33	5.53	6.64	7.24
NFC	1512.18**	35588.66**	1444.76	47767.03**	7208.48	1939.98	14.83	17.19
FC	25217.4^{ns}	24267.80**	12764.63	114948.65^{ns}	12636.9	13526.17	18.94	19.5
ADF	2979.91**	9902.70**	910.06	89670.61*	2604.56	1333.79	7.35	8.89
NDF	27325.29^{ns}	19648.18**	12847.8	109970.59^{ns}	12627.6	13477.76	17.5	17.92
HEM	1235.91**	22803.51*	2323.54	6314.08**	4373.55	2077.41	21.17	20.01
CEL	4365.27**	102143.81**	1836.48	25652.83*	2943.36	1642.55	13.63	12.89
LIG	868.34**	2898.07**	272.06	12999.93**	630.06	286.57	13.48	13.84
A+B1	4059.23**	31079.64**	1955.21	78950.02**	9729.47	2377.12	16.89	18.62
Frac B2	6626.53**	56658.91**	11190.55	139929.50^{ns}	16387.6	19845.88	26.67	26.25
Frac C	7823.44**	25600.00**	2363.31	98892.36**	5262.14	2435.03	13.93	14.14
TDN	4413.95**	10580.54**	1094.56	58526.48^{ns}	1951.96	1662.06	6.76	8.33
DMCLW	0.06**	0.20**	0.05	0.69^{ns}	0.07	0.04	11.72	11.07
DIGDM	1019.72**	5627.85**	458.39	49196.81**	1361.35	586.24	3.75	4.25
RVF	26.31^{ns}	195.70**	43.58	201.18**	29.73	33.53	0.78	0.69

^{ns} not significant; **; * significant at 1% and 5% probability by the F test, respectively.
DF: degree of freedom; DM: dry matter; NH_3-N: ammoniacal nitrogen (% of total N); pH: hydrogen potential; MM: mineral matter; OM: organic matter; CP: crude protein; NDIN: neutral detergent insoluble nitrogen; ADIN: acid detergent insoluble nitrogen; EE: ether extract; NFC: non-fibre carbohydrates; FC: fibre carbohydrates; ADF: acid detergent fibre; NDF: neutral detergent fibre; HEM: hemicellulose; CEL: cellulose; LIG: lignin; A+B1: A+B1 fraction of carbohydrates; Frac B2: B2 fraction of carbohydrates; Frac C: C fraction of carbohydrates; TDN: total digestible nutrients; DMCLW; dry matter consumption as a percentage of live weight; DIGDM: digestible dry matter; RVF: relative value of forage

Table 2. Nutritional analyses with an R^2 > 0.6 in regression analyses of silages obtained from four sorghum materials at different fermentation times

Materials (M)	Times (T) 0	1	3	7	14	28	56	112	224	Statistic L	Q	Equation	R^2
NH_3-N (% of total N)													
Qualysilo	1.53b	1.75b	2.74b	2.99b	3.06b	3.26b	3.61b	3.87b	3.99d	0	0	1	0.72
Chopper	1.67b	2.06ab	3.46a	3.38ab	3.51ab	3.82ab	4.56a	4.7a	11.57a	0	0	2	0.93
Maxisilo	2.47a	2.6a	2.93ab	3.79a	3.97a	4.13a	4.86a	5.07a	8.53b	0	0.966	3	0.92
Dominator	1.64b	2.58a	3.43a	3.76a	3.87a	3.93a	4.31a	4.49ab	5.06c	0	0	4	0.64
pH													
Qualysilo	5.17ab	4.94b	4.34a	4.10 a	3.93 a	3.74 a	3.65 a	3.59a	3.34a	0	0	5	0.66
Chopper	4.94bc	4.32c	3.99b	3.64bc	3.51b	3.48ab	3.45 a	3.42 a	3.36 a	0	0	6	0.47
Maxisilo	4.87c	5.31 a	3.84b	3.50c	3.43b	3.40b	3.37 a	3.34 a	3.33 a	0	0	7	0.4
Dominator	5.24a	4.92b	4.01ab	3.83 ab	3.69ab	3.63ab	3.56 a	3.48 a	3.42a	0	0	8	0.51
Cellulose													
Qualysilo	257.49b	302.57ab	270.22a	241.44b	276.03a	266.05ab	295.87ab	308.78a	539.08ab	0	0	9	0.96
Chopper	289.21b	233.04b	281.19a	216.36b	246.86a	238.19b	219.14b	335.86a	464.52b	0	0.003	10	0.86
Maxisilo	390.84a	352.93a	336.21a	358.74a	308.45a	336.78a	361.36a	332.81a	561.53a	0	0	11	0.9
Dominator	261.13b	255.52b	281.06a	251.85b	249.75a	264.10ab	263.64bc	352.35a	519.29ab	0	0.007	12	0.98
Lignin													
Qualysilo	147.76a	106.99ab	146.69a	152.43a	130.07a	136.43a	168.90a	162.04a	113.68a	0.219	0	13	0.52
Chopper	103.09b	78.36b	95.99c	72.69c	84.96b	93.98b	98.65c	117.01b	119.77a	0	0.276	14	0.6
Maxisilo	135.40a	112.72a	113.43bc	117.37b	105.92ab	114.86ab	137.17b	141.89ab	125.23a	0.097	0.33	15	0.42
Dominator	127.52ab	127.24a	135.32ab	113.89b	109.78ab	119.46ab	170.56a	144.77ab	122.49a	0.401	0	16	0.39
DIGDM (g / kg)													
Qualysilo	573.31a	569.95bc	564.23ab	582.17b	572.65b	575.47bc	526.95bc	546.04ab	545.23ab	0.010	0.051	17	0.60
Chopper	583.40a	646.42a	595.18a	663.83a	630.51a	630.24a	642.04a	577.62a	578.94a	0.000	0.721	18	0.28
Maxisilo	522.55b	526.26c	538.73b	518.11c	566.20b	537.17c	497.55c	519.21b	518.33b	0.152	0.271		-
Dominator	586.24a	590.83b	564.64ab	604.08b	608.93ab	590.21ab	550.76b	544.23ab	543.42ab	0.000	0.063	19	0.63
DE (Kcal / kg MS)													
Qualysilo	2273.25a	2204.09b	2087.65ab	2244.48b	2129.83bc	2161.28b	1632.12bc	1828.96ab	1784.33ab	0.002	0.027	20	0.72
Chopper	2304.47a	3019.62a	2391.43a	3131.93a	2757.16a	2741.33a	2877.91a	2156.79a	2163.05a	0.000	0.988	21	0.34
Maxisilo	1548.71b	1618.75c	1674.97b	1454.32c	1953.18c	1625.93c	1211.42c	1421.42b	1419.30b	0.072	0.157	22	0.19
Dominator	2415.42a	2449.89b	2061.69ab	1454.32b	2549.94ab	2326.39ab	1867.90b	1796.96ab	1798.95ab	0.000	0.018	23	0.71

(1)$Y=2{,}30+0{,}02689x-0{,}000088x^2$; (2)$Y=2{,}85+0{,}0117x-0{,}000118x^2$; (3)$Y=3{,}091+0{,}0237x$; (4) $Y=2{,}945+0{,}0266x-0{,}000079x^2$; (5) $Y=4{,}55-0{,}0182x+0{,}000058x^2$; (6) $Y=4{,}14-0{,}0148x+0{,}000052x^2$; (7)$Y=4{,}27-0{,}0197x+0{,}000071x^2$; (8)$Y=4{,}43-0{,}0188x+0{,}000065x^2$; (9)$Y=272{,}1-0{,}3057x+0{,}006648x^2$; (10)$Y=249{,}65-0{,}1227x+0{,}004964x^2$; (11)$Y=358{,}26-1{,}0424x+0{,}008659x^2$; (12)$Y=257{,}26+0{,}2042x-0{,}004372x^2$; (13)$Y=133{,}08+0{,}6364x-0{,}003228x^2$; (14)$Y=87{,}89+0{,}1650x$; (15)$Y=114{,}90+0{,}3744x-0{,}001446x^2$; (16)$Y=120{,}73+0{,}5671x-0{,}002510x^2$; (17)$Y=574.98-0.5508x+0.001888x^2$; (18)$Y=627.96-0.2326x$; (19)$Y=593.78-06311x+0.001796x^2$; (20)$Y=4828.96-3.3080x+0.010685x^2$; (21)$Y=4765.45-2.7318x+0.009542x^2$; (22)$Y=4767.16-3.6306x+0.013028x^2$; (23)$Y=4832.76-3.3784x+0.011655x^2$

Table 3. Chemical analysis with an $R^2 < 0.6$ in regression analyses of silages obtained from four sorghum materials at different fermentation times

Materials (M)	Times (T)									R^2
	0	1	3	7	14	28	56	112	224	
					Dry matter (g / kg)					
Qualysilo	352.6a	343.3a	292.5a	333.9a	335.1a	326.6a	327.5a	327.1a	331.1a	-
Chopper	313.3b	344.9a	306.5a	307.1ab	320.1ab	316.6a	325.1ab	308.3ab	312.4ab	-
Maxisilo	249.0c	246.7c	252.3b	272.8c	277.4c	234.7c	270.2c	259.1c	263.2c	-
Dominator	292.3b	310.3b	291.0a	292.2bc	289.5bc	283.5b	295.1bc	293.1b	297.2b	-
					Mineral matter (g / kg)					
Qualysilo	57.16b	59.20 b	59.50 b	67.18 ab	65.18 b	60.56 b	61.40 b	59.62 b	64.55 b	-
Chopper	74.61 a	62.76 b	66.19 b	63.79 ab	60.51 b	62.95 b	62.02 b	62.83 b	63.26 b	-
Maxisilo	81.11 a	80.28 a	80.45 a	73.20 a	81.35 a	80.46 a	80.89 a	80.79 a	79.00 a	-
Dominator	63.21 b	60.91 b	66.11 b	62.01 b	59.34 b	62.03 b	65.16 b	63.39 b	59.31 b	-
					Organic matter (g / kg)					
Qualysilo	942.83 a	940.80 a	940.50 a	932.82ab	934.81 a	939.44 a	938.60 a	940.38 a	935.45 a	-
Chopper	925.39 b	937.24 a	933.81 a	936.20ab	939.48 a	937.05 a	937.98 a	937.17 a	936.74 a	-
Maxisilo	918.89 b	919.71 b	919.55 b	926.80 b	918.64 a	919.53 b	919.11 b	919.21 b	921.00 b	-
Dominator	936.78 b	939.09 a	933.89 a	937.99 a	940.57b	937.94 a	934.83 a	936.61 a	940.68 a	-
					NDIN (g / kg total N)					
Qualysilo	494.42a	389.76a	390.05a	277.26ab	346.07a	351.64a	281.46a	373.78a	391.95a	0.17
Chopper	338.48bc	260.31b	332.45a	162.47bc	187.53b	205.95bc	151.34b	228.79b	230.44b	0.22
Maxisilo	255.57c	257.74b	172.35b	149.62c	313.43a	173.09c	249.29ab	218.67b	222.19b	-
Dominator	415.16ab	328.68ab	407.06a	300.99a	332.79a	297.99ab	232.38ab	301.51ab	318.84ab	0.44
					ADIN (g / kg total N)					
Qualysilo	470.24a	413.37a	417.29a	418.36a	364.72a	329.03a	318.94a	401.22a	435.59a	0.4
Chopper	290.37b	166.63b	229.03b	216.99b	243.84b	200.86bc	298.10a	315.53b	283.33bc	0.44
Maxisilo	302.57b	202.98b	225.37b	287.52b	214.20b	162.90c	204.71b	231.46c	257.62c	0.18
Dominator	521.86a	425.63a	275.41b	397.89a	344.11a	281.45ab	330.29a	367.34ab	355.46ab	0.11
					Ether extract (g / kg)					
Qualysilo	25.81c	33.11c	31.75bc	28.28a	28.43b	28.13b	28.09b	28.05b	28.01b	-
Chopper	39.90a	34.51bc	46.41a	27.21a	35.64a	38.21a	38.15a	38.10a	38.04a	-
Maxisilo	29.62bc	40.35a	28.17c	28.93	27.24b	30.53b	30.49b	30.44b	30.40b	-
Dominator	31.37b	37.82ab	35.44b	28.32a	38.30a	31.65b	31.60b	31.56b	31.51b	0.08
					Total Carbohydrates (g / kg)					
Qualysilo	857.02a	849.53a	854.60a	849.08b	847.57a	848.01a	837.11a	850.61a	848.99a	-
Chopper	823.65b	843.10a	828.68b	851.89ab	848.04a	835.48ab	825.33a	837.37a	839.30a	-
Maxisilo	829.91b	837.37a	851.03a	865.92a	F	824.82b	829.97a	838.15a	839.70a	0.11
Dominator	833.63b	841.82a	838.82ab	851.85ab	845.69a	840.73ab	833.26a	840.33a	845.02a	-
					NFC (g / kg)					
Qualysilo	192.27a	238.72a	298.92a	313.24b	286.79a	272.51a	264.37b	253.37a	278.44ab	-
Chopper	187.82a	279.16a	138.40c	394.08a	340.01a	296.45a	388.48a	286.23a	351.02a	0.17

Maxisilo	118.04a	118.84b	232.73ab	213.33c	273.77a	227.28a	249.01b	217.07a	223.33b	0.19
Dominator	177.92a	239.55a	165.92bc	306.42b	296.52a	280.92a	278.19b	286.65a	259.03b	0.26
Acid Detergent Fibre (g / kg)										
Qualysilo	405.26b	409.56ab	416.91ab	393.87b	406.10a	402.48ab	464.76ab	440.25ab	441.29ab	0.38
Chopper	392.30b	311.40c	377.17b	289.05c	331.82c	332.17c	317.02c	399.72c	398.02b	0.28
Maxisilo	526.24a	465.65a	449.65a	476.11a	414.38a	451.64a	502.50a	474.70a	475.83a	-
Dominator	388.65b	382.76b	416.38ab	365.75b	359.52ab	383.56bc	434.20b	442.58ab	443.62ab	0.53
Hemicellulose (g / kg)										
Qualysilo	312.02a	240.23a	186.66b	194.44a	217.24a	232.30a	188.99a	215.64a	201.86a	-
Chopper	288.55ab	282.53a	346.43a	210.99a	223.84a	254.08a	170.76a	204.04a	171.49a	0.54
Maxisilo	224.67b	282.99a	206.09b	211.46a	225.63a	195.82a	157.24a	202.50a	204.62a	0.36
Dominator	318.05a	261.70a	314.81a	232.93a	247.43a	230.44a	183.98a	168.39a	187.51a	0.79
Frac C (g / kg)										
Qualysilo	413.80a	302.59ab	412.06a	431.75a	368.29a	386.52a	483.96ab	457.16a	321.27a	0.53
Chopper	300.34b	222.98b	277.98c	204.79c	240.38b	269.92b	286.86c	335.35b	342.50a	0.55
Maxisilo	394.13a	323.19a	319.79bc	325.29b	300.44ab	334.52ab	396.67b	406.23ab	358.09a	0.4
Dominator	367.64ab	362.74a	387.12ab	321.09b	311.45ab	341.20ab	491.63a	413.60ab	347.86a	0.38
A+B1 (g / kg)										
Qualysilo	219.65a	261.52a	318.37a	324.54b	288.56ab	277.57a	261.56b	258.02ab	269.30ab	-
Chopper	198.74ab	313.78a	149.97b	423.98a	356.98a	313.77a	422.57a	295.75a	337.73a	0.11
Maxisilo	110.28b	120.80b	238.58ab	212.88c	265.43b	227.86a	216.57b	205.37b	203.17b	-
Dominator	187.82ab	257.61a	157.13b	317.68b	304.72ab	292.72a	241.14b	295.76a	277.28ab	-
RVF										
Qualysilo	74.46ab	82.57a	84.06a	89.05b	85.74ab	84.37ab	76.85b	77.59ab	78.95b	-
Chopper	80.31a	89.44a	76.92a	124.15a	94.93a	93.21a	122.5a	89.18a	94.63a	0.08
Maxisilo	64.77b	65.58b	76.57a	70.23c	73.19b	77.30b	69.88b	71.53b	70.90b	-
Dominator	77.38ab	85.73a	72.13a	92.36b	91.40a	89.66ab	83.34b	83.04ab	80.43ab	-

NDIN: neutral detergent insoluble nitrogen; ADIN: acid detergent insoluble nitrogen; NFC: non-fibre carbohydrates; Frac C: C fraction of carbohydrates; A+B1: A+B1 fraction of carbohydrates; RVF: relative value of forage

Table 4. Pearson's linear correlation between chemical and nutritional characteristics of sorghum silages

	NH3-N	pH	ADIN	CT	NFC	FC	ADF	NDF	LIG	A+B1	Frac B	Frac C	TDN	DMCLW	DIGDM	DE	RVF
DM	-0.18*	0.11	0.33**	0.30**	0.34**	-0.30**	-0.39**	-0.18*	0.11	0.30**	-0.27**	-0.01	0.21*	0.21*	0.38**	0.42**	0.16
NH_3-N		-0.62**	-0.56**	0.09	-0.65**	0.62**	0.14	-0.09	0.15	0.30**	-0.20*	0.05	0.05	0.16	-0.17*	-0.22**	-0.31**
pH			0.60**	-0.25**	-0.54**	-0.53**	-0.03	0.17*	-0.16	-0.48**	0.32**	0.02	-0.15	-0.29**	0.07	0.16	0.33**
ADIN				0.10	0.43**	-0.37**	-0.12	0.02	0.19*	-0.15	-0.14	0.26**	-0.17*	-0.12	0.12	0.21*	0.19*
CT					-0.20*	0.36**	0.03	-0.08	0.19*	0.39**	-0.36**	0.09	0.003	0.10	-0.08	-0.07	-0.18*
NFC						-0.97**	-0.45**	-0.06	-0.26**	-0.08	0.21**	-0.27**	0.27**	0.04	0.50**	0.55**	0.45**
FC							0.44**	0.08	0.23**	0.12	-0.22**	0.26**	-0.27**	-0.08	-0.49**	-0.53**	-0.40**
ADF								0.39**	0.32**	-0.48**	-0.006	0.61**	-0.72**	-0.51**	-0.95**	-0.95**	-0.47**
NDF									-0.34**	-0.52**	0.37**	0.17*	-0.58**	-0.89**	-0.40**	-0.39**	0.50**
LIG										0.20*	-0.80**	0.83**	-0.36**	0.29**	-0.32**	-0.31**	-0.65**
A+B1											-0.67**	-0.22**	0.58**	0.75**	0.46**	0.43**	-0.22**
Frac B												-0.54**	0.07	-0.48**	0.001	0.002	0.46**
Frac C													-0.78**	-0.28**	-0.60**	-0.57**	-0.36**
TDN														0.71**	0.72**	0.70**	0.04
DMCLW															0.52**	0.50**	-0.45**
DIGDM																0.99**	0.52**
DE																	0.53**

DF: degree of freedom; DM: dry matter; NH_3-N: ammoniacal nitrogen (% of total N); pH: hydrogen potential; MM: mineral matter; OM: organic matter; CP: crude protein; NDIN: neutral detergent insoluble nitrogen; ADIN: acid detergent insoluble nitrogen; EE: ether extract; NFC: non-fibre carbohydrates; FC: fibre carbohydrates; ADF: acid detergent fibre; NDF: neutral detergent fibre; HEM: hemicellulose; CEL: cellulose; LIG: lignin; A+B1: A+B1 fraction of carbohydrates; Frac B2: B2 fraction of carbohydrates; Frac C: C fraction of carbohydrates; TDN: total digestible nutrients; DMCLW; dry matter consumption as a percentage of live weight; DIGDM: digestible dry matter; RVF: relative value of forage

In carbohydrate fractions, fraction C was lower in Chopper silages at practically all times studied, while fraction A+B1 was lower in Maxisilo silage (Table 2). Since carbohydrate fractions are based on their rate of degradation (Du *et al.,* 2020), their study in high-inclusion feeds, such as silages, is essential. This is because the A+B1 fraction is soluble and offers rapid ruminal degradation (Sniffen *et al.,* 1992); it is the main source of energy for ruminal microorganisms that use non-fibrous carbohydrates (Perim *et al.,* 2014). Fraction A is rapidly fermented in the rumen by bacteria and is composed mainly of water-soluble sugars, organic acids, and short chain oligosaccharides (Du *et al.,* 2020), whereas fraction B1 indicates soluble fibre, starch, and pectin and has a slower digestion rate than fraction A (Du *et al.,* 2020). However, for the proper use of these fractions, they must be coordinated with the availability of nitrogen compounds for the synthesis of microbial protein.

The B2 fraction was higher in Maxisilo silages (447 g/kg) and lower in Qualysilo silage (329 g/kg) while Chopper (409 g/kg) and Dominator (370 g/kg) silages were similar (data presented only in the text). This fraction provides energy slowly in the rumen and can affect the efficiency of microbial synthesis and animal performance (Perim *et al.,* 2014) when present in high proportions in the diets. The main components of fraction B2 are cell wall degradable carbohydrates, which, despite a slow rate of digestion (Du *et al.,* 2020), are considered as potentially digestible fibre fractions in the rumen (Brandstetter *et al.,* 2019).

Fraction C was lower in the silages of the Chopper hybrid (Table 2), indicating a silage of better nutritional quality. Fraction C corresponds to unavailable fibre fractions and lignin (Brandstetter *et al.,* 2019), representing the cell wall carbohydrates unavailable for ruminal use (Du *et al.,* 2020). Increases in this fraction in feed are related to lower NDF digestibility and, consequently, there is a greater potential for this to have a filling effect (Brandstetter *et al.,* 2019).

The digestibility of DM was higher in the Chopper silage and lower in the Maxisilo silage (Table 2). As digestibility is directly affected by CP, NDF, and lignin, the less digestible silage was obtained with the Maxisilo hybrid, precisely due to the lower CP and higher lignin than the other hybrids (Table 2). As NFC and A+B1 fractions also have a direct relationship with digestibility (Du *et al.,* 2020), due to the higher content of these fractions in the Chopper silage, greater digestibility was also observed in this silage (Table 2). Digestibility declined linearly over time in Chopper silage and a quadratic response was observed in Qualysilo and Dominator silages (Table 2). These changes are due to the consumption of NFC, especially fraction A, which due to its content of water-soluble sugars, organic acids, and short chain oligosaccharides (Du *et al.,* 2020), is used as a substrate for fermentation inside the silo.

RVF is a quality indicator used when referring to the concentration of constituents of the plant cell wall (Gayer *et al.,* 2019). Chopper provided silage with the best RVF (96.15%) and Maxisilo with the smallest (71.11%). Qualysilo (81.52%) and Dominator (83.94%) produced silages with intermediate and statistically similar RVF (data not shown in tables). The results found are explained by the proportion of carbohydrates in the silages, since the higher the cellulose, hemicellulose and lignin content, the lower the feed RVF, indicating lower or higher quality materials (Gayer *et al.,* 2019). These fractions correspond to the fibrous carbohydrates in the food, which contain fractions B2 and C, which, due to their slow digestion (Du *et al.,* 2020) and practically non-existent content (Brandstetter *et al.,* 2019), respectively, give the forage a low nutritional value, as evidenced by the low RVF.

Digestible energy (DE) was lower in Maxisilo silage due to its higher content of fibrous constituents and lower content of rapidly fermentable carbohydrates (fractions A+B1) (Table 2). Since these carbohydrates are an important source of digestible energy in food, even in silages with desirable low levels of lignin, without the presence of fermentable carbohydrates, digestibility and DE will be low (Hristov *et al*., 2019).

The higher the DM content, the lower the NH_3-N of the silages (Table 2), since adequate DM content inhibits proteolysis inside the silo with the lowest NH_3-N production (Kung *et al*., 2018). This parameter in turn was negatively correlated with pH (-0.61**), ADIN (-0.56**), NFC (-0.65**), DMDIG (-0.17*), DE (-0.22**), and RVF (-0.31**) (Table 4). As NH_3-N is the result of proteolysis inside the silo, intensified by the delay in pH reduction and this is dependent on the fermentation of NFC by lactic acid bacteria (Muck *et al*., 2018), the listed correlations confirm the direct or indirect relationship between NFC and the nutritional quality of silages.

The increase in NH_3-N caused a reduction in ADIN in silages, confirming that proteolysis was not necessarily related to the Maillard reaction, whose main predisposing factor is temperature during fermentation (McDonald *et al*., 2010). ADIN showed a positive correlation (0.60**) with pH, indicating that failures in the production of silages that impair the initial fermentation and rapid reduction in pH contribute to the unavailability of N due to its complexation with ADF. The higher the content of NFC, the greater the initial fermentation of the silage and the faster its stabilization (Driehuis *et al*., 2018) by reducing the pH (-0.54**), providing silages of greater nutritional value, as confirmed by the positive correlation between NFC and DMDIG (0.50**), DE (0.55**), and RVF (0.45**) (Table 4).

The ADF showed a strong, positive correlation with fraction C (0.83**) and negative with TDN (-0.72), DIGDM (-0.95**), and DE (-0.95**) (Table 4). This is explained by the fact that they are inversely proportional. The smaller the insoluble fractions of the fibre, such as fraction C, a component of the ADF, the greater the availability of soluble fractions (Brandstetter *et al*., 2019).

The negative correlation between NDF and DMCLW (-0.89**) (Table 4) is due to the fact that silages with NDF levels close to or above 50% of DM can act as food consumption-limiting factors, characterizing the rumen-fill effect (Krämer-Schmid *et al*., 2016). As observed in the current study, the Maxisilo sorghum hybrid showed an NDF of approximately 73% of DM, corroborating this negative correlation.

The positive correlations between TDN and DMCLW (0.71**), DIGDM (0.72**), and DE (0.70**); and between DIGDM and TDN (0.99 **) (Table 4) are explained by the fact that the greater the amount of digestible nutrients (represented by TDN) the better the digestibility of the food (DIGDM) (Du *et al*., 2020), and consequently the more DE is available to the animal. High content of TDN enables a higher ruminal passage rate, thus increasing the DMCLW (McDonald *et al*., 2010). In the fractions of carbohydrates, the A+B1 fraction stood out with a positive correlation with DMCLW (0.75**).

Conclusion

The sorghum hybrids studied showed distinct nutritional characteristics. The production of silage from these sorghums can be carried out, as they all fit into the nutritional profiles proposed by the literature, characterizing them as good quality silages. It is noted that the Chopper hybrid performed better, due to better digestibility levels, which may result in greater animal performance.

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Author's Contributions

DDC and RHK were in charge of project design and writing of the manuscript. CRS, GM, AL, and GBR were in charge of project implementation. All co-authors participated in results, statistics, and interpretation of the study.

Conflict of Interest Declaration

The authors declare no conflict of interest.

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