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Chemical Composition, Fermentation Parameters and Losses of Silages From Different Hybrids of Biomass Sorghum

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ABSTRACT

Due to their high productivity, biomass sorghum (*Sorghum bicolor* (L.) Moench) hybrids may be promising to maximise roughage production for ruminants. However, the variation in chemical composition among hybrids may impact the nutritional value and the fermentation process of the silages produced. Thus, the present study assessed the fermentation quality and chemical composition of silages from five hybrids of biomass sorghum. The experiment adopted a 5 × 2 factorial randomised block design with five biomass sorghum hybrids (CMSXS5039, CMSXS5044, CMSXS7102, CMSXS7103 and BRS 716) sowed in two municipalities of the state of Mato Grosso do Sul, Brazil (Dourados and Jateí). The parameters assessed were chemical composition, in vitro dry matter digestibility, profile of short-chain organic acids, pH, ammonia, fermentation losses and aerobic stability. The silages produced from CMSXS7102, CMSXS7103 and BRS 716 in Dourados had higher fibre content and lower digestibility coefficients. In contrast, hybrids with higher non-fibrous carbohydrate content and lower lignin levels, such as CMSXS5044 and CMSXS5039, exhibited the best digestibility values. Silages produced in Jateí had higher moisture content, which resulted in increased effluent losses, particularly for the CMSXS5044 (450 kg ton^{-1} DM) and CMSXS5039 (320 kg ton^{-1} DM) hybrids. This higher effluent production in Jateí led to lower soluble protein (SP) and degradable protein (DP) concentrations compared to the silages from Dourados. Additionally, the higher moisture content in Jateí promoted the production of butyric acid in the silages. Silages from the CMSXS5039 hybrid (70.5 g kg^{-1} DM) had the highest lactic acid content; however, no significant difference was observed in acetic acid levels between the treatments. Overall, all the sorghum biomass hybrids tested produced silages with good fermentative and nutritional quality, but CMSXS5039 stood out in most of the parameters evaluated.

1 | Introduction

The development of forage plants with high potential for dry mass production per unit of area and with good nutritional value has been the goal of many researchers (Ramos et al. 2021). With the changes in global climate scenarios, the importance of cultures tolerant to water stress, such as sorghum (*Sorghum bicolor* (L.) Moench), has been growing, particularly in tropical and semi-arid regions (Orrico Junior et al. 2015). The main advantage of sorghum over maize (*Zea mays* L.; corn) is that it is adapted to diverse soil conditions, including shallow, saline and low-fertility soils (Getachew et al. 2016). Furthermore, sorghum stands out for its lower production costs (Buffara et al. 2018) and the exploitation of regrowth biomass (extra forage production).

The Brazilian Agricultural Research Corporation (*Empresa Brasileira de Pesquisa Agropecuária*—Embrapa) has been working towards the genetic improvement of biomass sorghum hybrids (BRS 716 was the first to be released in 2014) with the purpose of co-generation of energy via direct burning of the biomass (Rocateli et al. 2012). Those sorghum hybrids have rapid growth and a mean production of 50 ton ha^{-1} of dry matter, much above commonly observed productions for other sorghum types (Rosa et al. 2022). Moreover, when sowed in the beginning of the planting season (late spring for the Center-West region of Brazil; November–December), biomass sorghum hybrids have good regrowth capacity after harvest, which enables a second harvest (fall; May–June) without requiring new sowing.

Rapid-growth forage plants tend to have higher proportions of structural components, especially at more advanced stages of development (Adesogan et al. 2019). de Queiroz et al. (2021) observed that the fibrous fraction concentrations of BRS 716 biomass sorghum increased linearly with plant maturity. However, the values found for lignin ranged from 7.01% to 9.98% (plants harvested between 70 and 160 days after sowing), which are close to those commonly observed for sorghum silages (Miron et al. 2007; Di-Marco et al. 2009; Santo et al. 2018). Such results show the potential for the use of biomass sorghum hybrids as roughage sources for ruminant production. However, when comparing sorghum hybrids used for biomass production, Rosa et al. (2022) found significant differences in the production and chemical composition of the plants, which, according to Alves et al. (2022), may significantly impact the fermentation quality of silages.

Based on the above, the hypotheses of this work were the following: (i) sorghum biomass hybrids can be used to produce silage with good fermentative and nutritional quality; (ii) silages from hybrids CMSXS5039, CMSXS5044, CMSXS7102 and CMSXS7103 (in the pre-launch phase) have a higher quality than silages produced by BRS 716 (commercial hybrid). Therefore, the present study aimed to assess the chemical composition and fermentation quality of silages from five hybrids of biomass sorghum to identify which of those are the most promising for silage production for livestock feeding.

2 | Materials and Methods

The trial was simultaneously conducted in two regions of the state of Mato Grosso do Sul, Brazil. The first region was a farm located in the municipality of Jateí (22°26′57″ S 54°20′11″ W), which has a soil type of Latossolo Vermelho Amarelo distroférrico—LVAd according to the Brazilian Soil Classification System—SiBCS (Santos et al. 2018) equivalent to Typic Hapludox, in the Soil Taxonomy (Soil Survey 2014), with 12% clay. The second region was the experimental area of Brazilian Agricultural Research Corporation located in the municipality of Dourados (22°16′44″ S 54°49′10″ W), which has a soil type of Latossolo Vermelho eutrófico—Lve according to the Brazilian Soil Classification System—SiBCS (Santos et al. 2018) equivalent to Rhodic Eutrudox, in the Soil Taxonomy (Soil Survey 2014), with 75% clay. The climate in both sites is Cwa (humid mesothermic, with wet summers) according to the Köppen classification (Fietz and Fisch 2008).

The experiment adopted a 5×2 factorial randomised block design comprising five biomass sorghum hybrids: CMSXS5039, CMSXS5044, CMSXS7102, CMSXS7103 (in the pre-launch phase) and BRS 716 (commercial hybrid) in two regions of the state of Mato Grosso do Sul, Brazil. Each experimental unit was made up of one silo. Six observations were performed per treatment for a total of 60 experimental units.

The hybrids were sown (4.5 seeds m^{-1}) in Jateí and Dourados on 5 and 23 November 2021, respectively, using an SHM 1517 planter with a 45-cm spacing between rows. For seeding fertilisation, 300 kg ha^{-1} of the 08-20-20 formula (N–P–K) was used in both areas. Topdressing was carried out 20 days after plant emergence with 140 kg ha^{-1} of ammonium sulphate in both areas, totalling 268 kg N ha^{-1}. A density of 100,000 plants ha^{-1} was determined for the sorghum. Each experimental plot was composed of seven 50 m rows. In Jateí, the sorghum was harvested at 124 days and, in Dourados, at 140 days after sowing.

For silage production, part of the central plants in each experimental plot was collected. Aiming at greater mass homogeneity, the sorghum plants were processed in a stationary forage grinder, which yielded a mean particle size of 1.5 cm. After that, the material of each plot was once again homogenised and used to fill the experimental silos. During filling, forage samples were collected from each treatment. The samples were frozen at −18°C for later analysis of chemical composition, pH and buffer capacity (Table 1).

The ground forage mass was stored in laboratory experimental silos built using PVC pipes (10-cm diameter and 50-cm height) with a useful volume of 3.8 L. The material was manually compacted using wood rods to achieve a mean density of 820 kg m^{-3} for the treatments. The bottom of each experimental silo had 300 g of sand for effluent drainage. A fine fabric mesh was used to keep the forage from touching the sand. After filling, the experimental silos were sealed with a double-faced (black and white) plastic film and adhesive tape and stored in the laboratory at room temperature.

The silos were opened after 150 days of storage, and the material inside them was removed and homogenised for sample collection. The samples of each of the silages were sent to the laboratory for chemical composition analysis. Another portion of the samples was frozen for later pH analysis. The dry samples were ground in a Willey mill, with a 1-mm mesh sieve and were scanned on a Foss 5000 Transport near-infrared reflectance spectrophotometer (NIRS) system (Eden Prairie, NY, USA). The spectra were processed using NIR calibrations (WinISI version 4.6.11, FOSS Analytical A/S, Denmark) obtained through the Dairy One Forage Laboratory (Ithaca, NY) to determine concentrations of dry matter (DM), mineral matter (MM), crude protein (CP), soluble protein (SP), digestible protein (DP), neutral detergent insoluble protein (NDIP), neutral detergent fibre (NDF), acid detergent fibre (ADF), lignin, 48-h NDF digestibility ($NDFD^{48}$), ether extract (EE), soluble carbohydrates (SC), non-fibre carbohydrates (NFC) and starch. The concentrations of lactic acid, acetic acid, butyric acid and ammonia nitrogen (NH_3–N) were also measured by NIRS but only in the silage samples.

TABLE 1 | pH, buffer capacity and chemical composition of the fresh forage (before ensiling) of the different sorghum biomass hybrids assessed in the municipalities of Jateí and Dourados, MS, Brazil.

	CMXS5039		CMXS5044		CMXS7102		CMXS7103		BRS 716	
Parameters	**Jateí**	**Dourados**	**Jateí**	**Dourados**	**Jateí**	**Dourados**	**Jateí**	**Dourados**	**Jateí**	**Dourados**
pH	5.37	5.01	5.42	5.46	5.54	5.37	5.42	5.03	5.33	5.54
BC, meq100 g^{-1} of DM	8.43	7.58	6.84	6.26	8.58	8.48	5.23	7.21	5.84	6.20
DM, g kg^{-1} of FM	192	215	199	217	201	237	212	229	230	234
MM, g kg^{-1} of DM	66.0	39.5	72.0	44.0	55.5	35.0	55.5	31.1	58.5	28.0
SC, g kg^{-1} of DM	85.0	89.0	75.0	77.5	67.5	68.5	71.0	66.1	75.5	77.5
EE, g kg^{-1} of DM	14.5	14.05	16.5	15.0	16.0	12.0	14.0	12.5	15.5	16.0
Starch, g kg^{-1} of DM	15.0	41.5	27.0	49.5	46.0	29.5	34.5	28.0	35.0	42.5
CP, g kg^{-1} of DM	129.1	78.5	146.0	93.0	114	70.0	113.0	83.0	118.5	79.0
SP, g kg^{-1} of CP	345	585	365	515	315	445	325	460	325	410
DP, g kg^{-1} of CP	590	790	600	695	550	635	580	630	570	630
NDIP, g kg^{-1} of CP	37.0	20.5	47.5	27.0	32.0	20.0	34.5	18.5	39.5	22.5
NDF, g kg^{-1} of DM	699	720	686	692	715	762	730	765	720	773
ADF, g kg^{-1} of DM	409	455	396	428	433	490	433	489	421	478
$NDFD^{48}$, g $kg^{-1}$of DM	690	545	695	565	665	535	665	540	670	520
Lignin, g kg^{-1} of DM	62.0	69.0	57.5	69.0	72.5	87.0	72.5	84.0	63.0	71.5
NFC, g kg^{-1} of DM	83.5	153.0	85.0	170.0	85.5	119	79.0	107	83.5	123

Abbreviations: ADF, acid detergent fibre; BC, buffer capacity; CP, crude protein; DM, dry matter; DP, digestible protein; EE, ether extract; FM, fresh matter; MM, mineral matter; NDF, neutral detergent fibre; $NDFD^{48}$, NDF digestibility at 48 h; NDIP, neutral detergent insoluble protein; NFC, non-fibre carbohydrates; pH, potential of hydrogen; SC, soluble carbohydrate; SP, soluble protein.

Part of the frozen samples was processed to produce an aqueous extract, which was used to assess pH (in the fresh forage and silage) and buffer capacity (only in the fresh forage). To obtain the aqueous extract, 25 g of the forage was diluted in 225-mL distilled water and manually homogenised for approximately 20 min. The pH of the extract was determined using a digital potentiometer (Tecnopon mPA-210 MS), and the buffer capacity was determined according to Playne and Mc Donald (1966).

All components of the experimental silos, as well as the ensiled forage, were weighed prior to ensiling and after 150 days of storage, which allowed calculating the gas losses, effluent production and dry matter recovery (Li et al. 2017). The determination of gas losses was calculated according to the following equation:

$$GL = \frac{(SWE - SWO)}{EDM} \times 1000$$

where GL = gas losses (g kg^{-1} DM); SWE = all components (silo, forage, sand, fabric and plastic film) weight at ensiling (kg), SWO = all components (silo, forage, sand, fabric and plastic film) weight at opening (kg); and EDM = ensiled dry matter (kg).

After removal of the silage, the whole set (silo, sand and fabric mesh) was weighed to quantify the amount of effluent produced. The determination of effluent production was calculated through the equation:

$$EP = \frac{(WSA - WSB)}{EDM} \times 1000$$

where EP = Effluent production (kg ton^{-1} of DM); WSA = weight of whole set (silo, sand and fabric) after opening (kg); WSB = weight of whole set (silo, sand and fabric) before opening (kg); and EDM = ensiled dry matter (kg).

The DM recovery was calculated through the equation:

$$DMR = \left\{1 - \left(\frac{IDM - FDM}{IDM}\right)\right\} \times 1000$$

where DMR = dry matter recovery (g kg^{-1} DM); IDM = initial dry matter (kg of ensiled DM); FDM = final dry matter (kg of DM removed from the silos).

Aerobic stability was determined in all silages after the silos were opened. Samples (2 ± 0.005 kg) of each replicate of each treatment were freely placed in the clean experimental silos. Temperature sensors were placed in the geometric centre of the silages, and a double layer of gauze was placed on top of each experimental silo to prevent drying and contamination while allowing for air penetration. Ambient temperature, as well as the temperature of each silage, was recorded every minute, and the average was calculated every 20 min using a datalogger RC-4, Elitech (San Jose, CA, USA). Aerobic stability was defined as the number of hours the silage remained stable before increasing by more than 2°C above the ambient temperature (Kung et al. 2018).

The data were analysed using the statistical program RStudio (R, 2009). When the interaction of factors was significant ($\alpha \leq 0.05$), the factors were read separately for analysis. In the case of non-significant interaction, the factors were analysed by principal component. The means were compared by Tukey's test at a 5% level of significance. The silage data were analysed according to the following model:

$$Y_{ijk} = \mu + S_i + SA_j + S^* SA_{ij} + \varepsilon_{ijk}$$

where Y_{ijk} = dependent variable, μ = overall average, S_i = effect of different hybrids (fixed effect; i = CMSXS5039, CMSXS5044, CMSXS7102, CMSXS7103 and BRS 716), SA_j = site effect (fixed effect; $j = D$ and J), $S * SA_{ij}$ = effect of the interaction between hybrids and sites and ε_{ijk} = random error associated with each observation.

3 | Results

A significant interaction ($p < 0.01$) between hybrids and sites was observed concerning the DM concentration of the silages studied (Table 2 and Figure 1). The silages produced in Jateí had lower DM values (187 g kg^{-1}) when compared with those produced in Dourados (235 g kg^{-1}). Dry matter values above 250 g kg^{-1} were only seen for treatments CMSXS7102 and CMSXS7103 grown in Dourados.

The site effect was found significant ($p < 0.01$) for concentrations of CP, SP, DP and NDIP. On average, the silages produced in Jateí had 27% higher CP concentrations than the silages produced in Dourados. However, silages from Dourados had higher proportions of SP and DP when compared with those from Jateí.

Hybrids CMSXS5044 and CMSXS5039 had the highest NH_3–N concentrations, 20.9% higher than the other hybrids tested on average. The silage production sites also influenced ($p < 0.01$) NH_3–N concentrations in the silages, with the highest values obtained from silages produced in Jateí.

There was a significant interaction for NDF and ADF concentrations of the silages as a function of hybrids and production sites (Figure 2). For Dourados, the NDF and ADF concentrations of the silages were similar among the hybrids tested, with higher values than those obtained in the silages produced in Jateí. The lowest NDF and ADF concentrations were observed in Jateí for hybrids CMSXS5044, CMSXS5039 and BRS 716. The NDF digestibility coefficients did not differ among the silages produced in Jateí, which had mean values above 632 g kg^{-1} of NDF. However, for Dourados, hybrid BRS 716 had the lowest NDFD^{48} coefficient (508 g kg^{-1} of NDF), about 21% lower than hybrid CMSXS7103 grown in Jateí. The interaction between hybrids and production sites was also observed for lignin concentrations, particularly hybrid BRS 716, which had the highest lignin content when the silage was produced in Dourados and one of the lowest lignin concentrations when produced in Jateí.

The NFC was lower ($p < 0.05$) for the silages produced in Dourados (all below 140 g kg^{-1} of DM), except for hybrids CMSXS7102 and CMSXS7103, which had low NFC concentrations in both production sites. Starch and MM concentrations did not differ ($p > 0.05$) among the treatments tested.

Hybrid CMSXS5044 had the lowest ($p < 0.01$) value of DM recovery (924 g kg^{-1} of the ensiled DM) among the hybrids tested. Dry matter recovery was also impacted by the site where the silages were produced, with lower ($p < 0.01$) values observed for the silages produced in Jateí.

There was an interaction ($p < 0.01$) between the hybrids and the production sites on the gas and effluent losses of the silages tested (Figure 1). The highest gas losses were observed for hybrid CMSXS5039 grown in Jateí and for hybrid CMSXS5044 grown at both sites. The silages produced in Dourados had lower gas losses, except for hybrid CMSXS5044, as previously described. Overall, the lowest ($p < 0.01$) effluent productions were obtained for the silages produced in Dourados, irrespective of the hybrid used. However, the silages from hybrids CMSXS5044 and CMSXS5039 produced in Jateí had the highest ($p < 0.01$) effluent productions.

No effect ($p > 0.05$) of site was observed on the pH of the silages assessed. An influence of hybrids ($p < 0.01$) was seen on pH values, with the lowest values obtained for hybrids CMSXS5044 and CMSXS5039 (3.73 and 3.76, respectively). Lactic acid production was numerically higher for hybrid CMSXS5044. However, no differences were observed when it was compared with hybrids CMSXS5039 and BRS 716. The silages from hybrids CMSXS7102 and CMSXS7103 had, on average, lactic acid concentrations 12.7% lower than those of hybrid CMSXS5044. No differences ($p > 0.01$) were observed in acetic acid concentrations among the treatments tested.

Butyric acid concentrations were influenced ($p = 0.04$) by the hybrids and production sites of the silages (Figure 1). The highest butyric acid productions were observed for the silages of hybrids CMSXS5044 and CMSXS5039 produced in Jateí, with the lowest butyric acid concentrations observed for the silages produced in Dourados irrespective of the hybrid tested.

Aerobic stability values of the silages ranged from 115 to 145 h, with those from hybrids CMSMS7103 and BRS 716 having the

TABLE 2 | Chemical composition, fermentation parameters and losses of silages from different sorghum biomass hybrids assessed in the municipalities of Jateí and Dourados, MS, Brazil.

	Hybrid						Site			p		
Parameters	**CMSXS 5039**	**CMSXS 5044**	**CMSXS 7102**	**CMSXS 7103**	**BRS 716**	**SEM**	**Dourados**	**Jateí**	**SEM**	**H**	**S**	**H*S**
DM, g kg^{-1} FM	215	193	219	225	203	2.17	235	187	1.43	<0.01	<0.01	<0.01
MM, g kg^{-1} DM	57.4	61.4	59.7	61.4	56.2	1.58	58.9	59.5	1.05	0.06	0.69	0.63
SC, g kg^{-1} DM	66.0	60.9	42.0	50.3	52.7	3.86	43.0	65.8	2.64	0.00	<0.01	<0.01
Starch, g kg^{-1}DM	51.4	39.9	44.6	46.3	50.8	3.74	44.4	48.8	2.37	0.19	0.20	0.47
CP, g kg^{-1} DM	105	106	103	103	107	1.49	88.6	121	0.94	0.22	<0.01	0.08
SP, g kg^{-1} of CP	639	640	628	624	623	10.2	64.6	61.7	7.69	0.45	<0.01	0.22
DP, g kg^{-1} of CP	771	785	774	771	782	8.51	81.4	73.9	5.82	0.65	<0.01	0.09
NDIP, g kg^{-1} of CP	17.9	17.0	19.6	20.0	22.7	0.74	17.0	22	0.53	0.07	<0.01	0.41
NH_3-N, g kg^{-1} of TN	93.0ab	110a	82.3b	87.3b	73.0b	0.50	70.0	11	0.31	<0.01	<0.01	0.37
EE, g kg^{-1} of DM	37.7	42.2	36.5	32.8	38.5	1.11	34.8	40.3	0.80	<0.01	<0.01	<0.01
NDF, g kg^{-1} of DM	653	657	692	689	672	5.64	707	641	3.56	<0.01	<0.01	0.03
ADF, g kg^{-1} of DM	408	413	435	434	415	4.23	450	392	3.19	<0.01	<0.01	<0.01
Lignin, g kg^{-1} of DM	60.8	58.4	72.2	69.7	73.9	1.45	79.9	54.0	0.91	<0.01	<0.01	<0.01
NFC, g kg^{-1} DM	149	133	111	119	130	5.53	115	142	3.71	<0.01	<0.01	0.04
$NDFD^{48}$, g kg^{-1} of NDF	591	585	578	590	573	4.13	535	632	3.17	<0.01	<0.01	<0.01
Lact, g kg^{-1} of DM	62.8ab	70.5a	61.8b	61.2b	63.6ab	2.31	62.8	65.2	1.49	0.04	0.23	0.07
Acet, g kg^{-1} of DM	19.0	22.2	19.1	22.5	19.2	1.45	21.4	19.4	0.91	0.22	0.11	0.09
But, g kg^{-1} of DM	0.67	0.75	0.15	0.25	0.25	0.11	0.09	0.74	0.08	0.00	<0.01	0.04
pH	3.76bc	3.73c	3.80ab	3.84a	3.79b	0.01	3.80	3.80	0.01	<0.01	0.88	1.00
EP, kg ton^{-1} DM	212	284	197	146	190	19.8	105	307	12.5	0.00	<0.01	0.01
GP, g kg^{-1} of initial DM	45.7	56	20.3	20.4	14.2	0.49	21.8	40.8	3.12	<0.01	<0.01	0.01
DMR, g $kg^{-1}$of initial DM	942a	924b	946a	957a	951a	4.19	960	928	2.6	<0.01	<0.01	0.29
AS, h	115b	122b	120b	143a	145a	15.3	122	134	19.6	0.03	0.07	0.54

Note: Means followed by different letters differ according to Tukey's test at a 5% probability.
Abbreviations: Acet, acetic acid; ADF, acid detergent fibre; AS, aerobic stability; But, butyric acid; CP, crude protein; DM, dry matter; DMR, DM recovery; DP, digestible protein; EE, ether extract; EP, effluent production; FM, fresh matter; GP, gas production; H, hybrid; Lat, lactic acid; MM, mineral matter; NDF, neutral detergent fibre; $NDFD^{48}$, NDF digestibility at 48 h; NDIP, neutral detergent insoluble protein; NFC, non-fibre carbohydrates; NH_3-N, ammoniacal nitrogen; pH, potential of hydrogen; S, site; SC, soluble carbohydrate; SEM, standard error of the mean; SP, soluble protein; TN, total nitrogen.

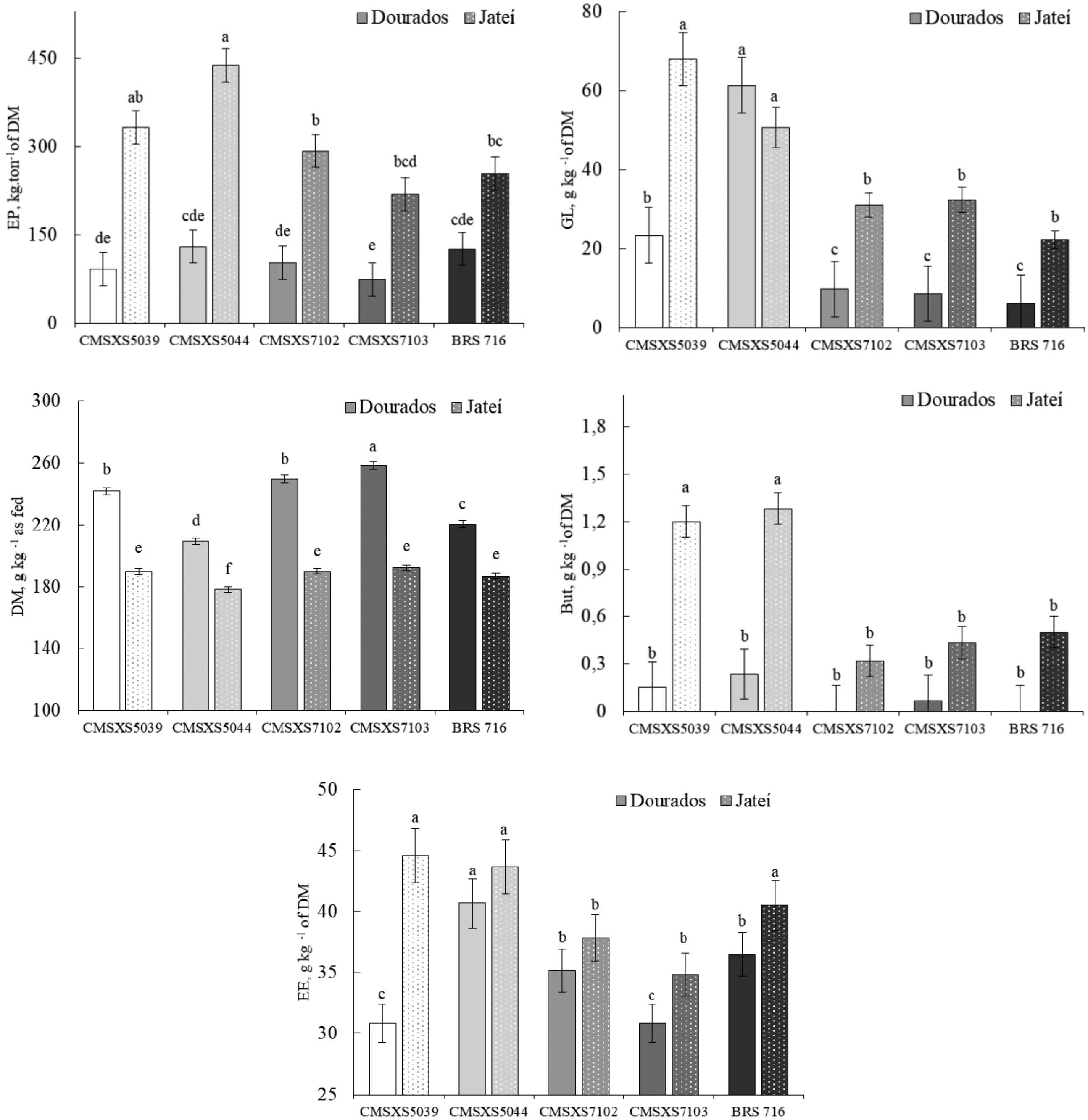

FIGURE 1 | Effluent production (EP), gas losses (GLs), DM concentrations, butyric acid (But) concentrations and ether extract (EE) concentrations of the silages from different sorghum biomass hybrids assessed in the municipalities of Jateí and Dourados, MS, Brazil. Means followed by different letters differ according to Tukey's test at a 5% probability.

highest values ($p = 0.03$). No significant differences were observed in aerobic stability of the silages between the municipalities assessed.

4 | Discussion

Biomass sorghum hybrids are long-cycle plants characterised by their low DM concentrations, particularly when harvested under 160 days of age (de Queiroz et al. 2021). However, bringing forward the harvest of long-cycle sorghum hybrids is a common practice in Brazil as it allows exploring plant regrowth prior to the dry season (fall–winter), thus increasing DM production with no need for a second sowing of the crop (Yonemaru, Kasuga, and Kawahigashi 2022).

In the present experiment, the plants were harvested at 124 and 140 days (GS2 stage—boot to half-bloom) of age in Jateí and Dourados, respectively, which resulted in effluent formation, especially for the silages produced in Jateí. The highest effluent productions observed for hybrids CMSXS5044 and CMSXS5039 grown in Jateí (450 kg ton^{-1} of DM) are due to their low DM concentrations at harvest. According to Orrico Junior et al. (2015), saccharine sorghum hybrids produce the highest volumes of

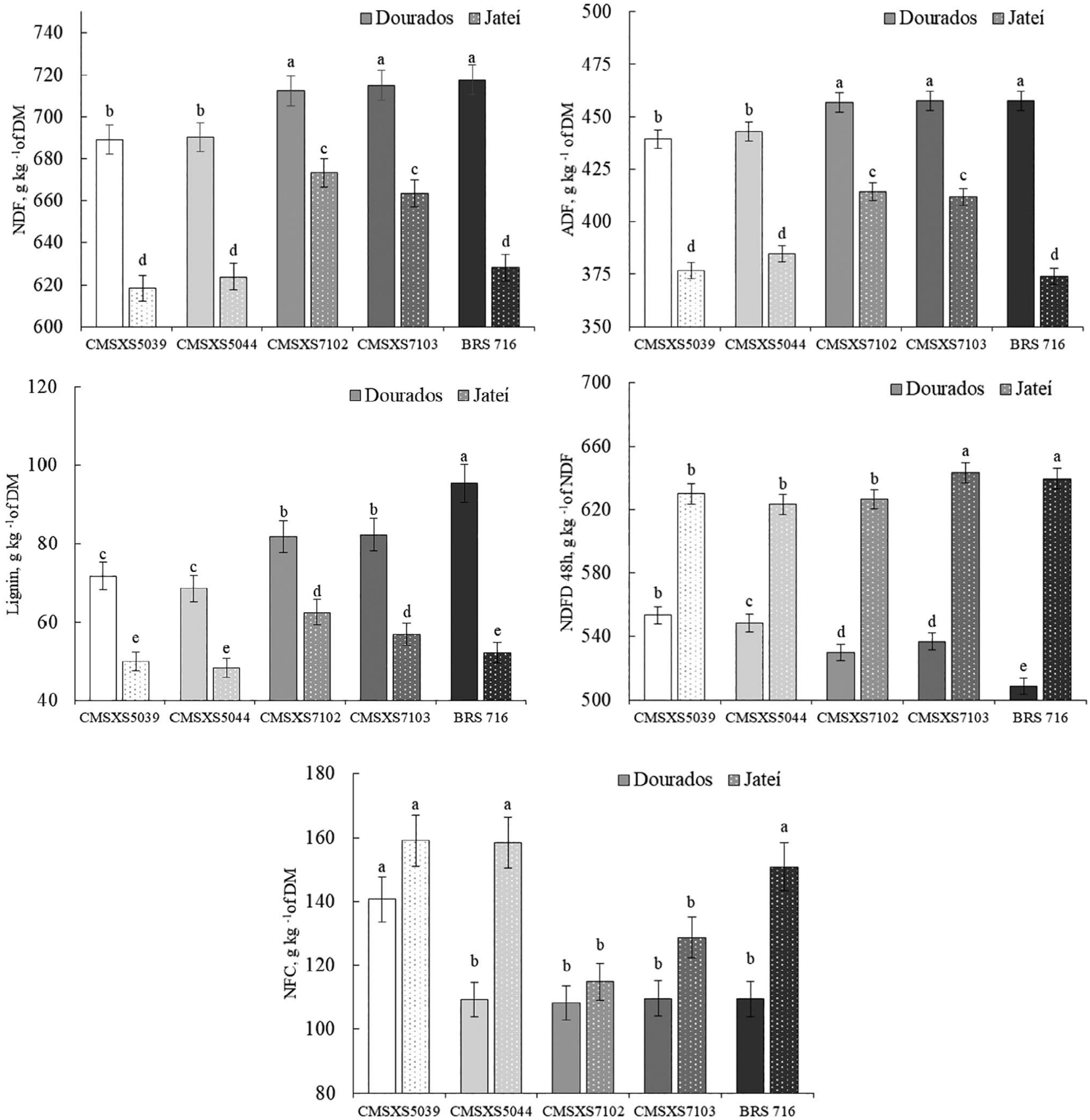

FIGURE 2 | Concentrations of neutral detergent fibre (NDF), acid detergent fibre (ADF), lignin, NDF digestibility at 48 h ($NDFD^{48}$) and non-fibre carbohydrates (NFC) of the silages from different sorghum biomass hybrids assessed in the municipalities of Jateí and Dourados, MS, Brazil. Means followed by different letters differ according to Tukey's test at a 5% probability.

effluent, which may surpass 521 kg ton^{-1} of DM. According to those authors, that is because saccharine hybrids have juicy stems, which leads to effluent formation. Despite lacking the juicy stems of the saccharine hybrids, biomass sorghum hybrids CMSXS5044 and CMSXS5039 have saccharine sorghum genes (R.A.C. Parrella, personal communication, 2023), which may have contributed to the high effluent productions obtained. Effluent release during silage production represents a loss of dry matter and a reduction in the value of the silage as food. Silage effluent has a high biochemical oxygen demand (BOD), nitrogen (N), phosphorus (P) and low pH (corrosive) (Gebrehanna et al. 2014). If discarded without treatment, it can impact the quality levels of surface and groundwater, which is why an adequate collection, treatment and disposal system is necessary (Gebrehanna et al. 2014). Therefore, the use of dry additives can be a way to improve DM levels (Alves et al. 2022) and significantly reduce the production of effluent from sorghum silage biomass.

In addition to having higher effluent losses, silages with DM content below 300 g kg^{-1} of DM may also favour the growth of bacteria of the genus *Clostridium* (Kung et al. 2018). Some species of the genus *Clostridium* are able to ferment sugars and lactic acid into butyric (saccharolytic) acid, while other species are highly proteolytic, resulting in silages with higher DM losses and higher NH_3–N and butyric acid concentrations (Muck 2010; Borreani et al. 2018; Kung et al. 2018). Indeed, higher gas, butyric acid and NH_3–N productions were observed in the silages with the highest moisture content. Nonetheless, the values for those parameters were within the limits recommended by Kung Jr et al. (2018). The low pH values and the high productions of organic acids observed were responsible for controlling the action of undesirable microorganisms during ensiling.

Several factors impact the final pH value of silage. However, the concentration of soluble carbohydrates and the buffer capacity of the culture are the most important ones (Borreani et al. 2018). As they have lower buffer capacity and higher soluble carbohydrate concentrations, silages of grains such as corn and sorghum have lower final pH (3.7–4.0) than silages of leguminous plants (4.3–5.0) (Kung et al. 2018). Lactic acid concentrations in well-preserved silages vary from 20 to 40 g kg^{-1} DM but can be considerably higher in silages with DM concentrations below 300 g kg^{-1} of DM at harvest (Kung et al. 2018). That may help explain the high lactic acid concentrations (above 60 g kg^{-1} DM) observed in this trial.

Another noteworthy detail was the higher soluble carbohydrate concentration observed both in the fresh forage and in the silage for hybrids CMSXS5044 and CMSXS5039. The participation of saccharine sorghum hybrids in the crossings that originated those biomass sorghum hybrids (R.A.C. Parrella, personal communication, 2023) likely contributed to those plants having higher sugar concentrations in their stems and, consequently, provided ideal conditions to increase lactic acid production.

High lactic acid production may also result in silages with low aerobic stability, with the presence of acetic acid being desirable at sufficient concentrations to ensure good aerobic stability. Acetic acid is the acid found at the second highest concentration in good quality silages, usually ranging from 10 to 30 g kg^{-1} DM (Borreani et al. 2018). According to Comino et al. (2014), acetic acid should be present at moderate concentrations in order to inhibit yeast growth without reducing intake by animals.

Similarly to lactic acid, acetic acid concentration is usually inversely related to the DM content in the forage. However, no significant differences in acetic acid concentrations were observed among the treatments. The low buffer capacity values and high soluble carbohydrate concentrations of the hybrids (Table 1) suggest that pH may have sharply dropped in the first days of ensiling, which may have favoured homolactic fermentation in the detriment of heterolactic fermentation.

According to a review by Wilkinson and Davies (2013), silages with non-dissociated acetic acid concentrations above 8 g kg^{-1} fresh silages are always stable under aerobic conditions, whereas those with concentrations below 3 g kg^{-1} fresh silage are not. Those values gain importance in situations where there is a relatively high yeast population in the silage and high residual sugar concentration that acts as a substrate, along with lactic acid for yeast growth. In the present experiment, the mean value converted was 3.5-g non-dissociated acetic acid per kg of silage, which would qualify a silage of reduced stability (Wilkinson and Davies 2013). Nevertheless, the aerobic stability of the treatments was moderate to high, with values ranging from 115 to 145 h. The antifungal properties of the polyphenols present in the sorghum plants may potentially be responsible for providing greater aerobic stability to the silages (Weinberg et al. 2011), thus justifying the values observed. Assessing the polyphenol concentrations in the present experiment, which was not done, might help explain the higher stabilities obtained by hybrids CMSXS7103 and BRS 716.

The silages produced in Jateí had much higher CP concentrations than values commonly reported in the literature for biomass sorghum hybrids (de Queiroz et al. 2021). It is likely that the more favourable environmental conditions of the municipality of Jateí and the early harvest contributed to the high CP concentrations observed. Cell wall components tend to increase significantly in sorghum plant biomass at the end of its production cycle (de Queiroz et al. 2021). Therefore, due to the dilution effect, CP concentration tends to decrease when sorghum is harvested at more advanced maturity stages (in Dourados). Another important point to consider is that sorghum biomass production increases with plant age until the grain-filling stage, which further contributes to the observed protein dilution effect.

Despite having the highest CP concentrations, the silages produced in Jateí had the lowest SP and DP proportions. The higher effluent productions likely led to the greater SP losses and, consequently, greater DP losses for the silages produced at that site. Orrico Junior et al. (2015), when studying five saccharine sorghum hybrids, showed that effluent production significantly reduces the fraction of soluble nutrients in the silages, besides decreasing their in vitro digestibility coefficients.

According to Adesogan et al. (2019) and Van Soest (1994), NDF, ADF and lignin concentrations increase with cell wall development, which is essential to provide structural support to the plants during growth. However, the concentrations of those fibrous fractions are also influenced by genetic and environmental factors (Santos et al. 2018). In the present experiment, it was clear that the silages produced in Jateí had the lowest concentrations of fibrous components and the highest $DNDF^{48}$ values. However, for the municipality of Dourados (at more advanced maturation stages), hybrids CMSXS5044 and CMSXS5039 had the lowest proportions of fibrous components and one of the highest $DNDF^{48}$ values. Those hybrids likely have lower lignin participation in cell wall thickening, which decreases the proportion of ester bonds between lignin and hemicellulose, thus improving forage digestibility (Van Soest 1994). The reduction in silage digestibility decreases animal productivity as the feed remains in the rumen for longer, possibly limiting DM intake. According to Oba and Allen (1999), increasing in vitro NDF digestibility by one unit results in a potential increase in DM intake by 0.17 kg day^{-1} and an increase in milk production by 0.25 kg day^{-1}, which places hybrids CMSXS5044 and CMSXS5039 as potentially more interesting from a nutritional standpoint.

5 | Conclusions

Overall, the biomass sorghum hybrids tested proved promising for silage production, with the only caveat being the high effluent productions when the plant is harvested at an early developmental stage. Among the hybrids tested, CMSXS5039 stood out for being high in both fermentation and nutritional quality of silage.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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