

Forage production, fermentation and nutritional value of silage from commercial sorghum varieties

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ABSTRACT

Objective: To evaluate forage yield, fermentation characteristics, and the nutritional quality of silage from five commercial sorghum (*Sorghum bicolor* (L.) Moench) varieties in comparison with forage corn.

Design/Methodology/Approach: The study assessed the impact of five sorghum varieties Super Sorgo, Silo Miel, Silo Master, Gigante Verde, and BMR sorghum alongside corn on forage yield, silage fermentation profile, and nutritional composition. A randomized complete block design with four replications was implemented for both field and silage trials. Data were analyzed using analysis of variance (ANOVA) with SAS software (version 9.3), with statistical significance declared at $P \leq 0.05$.

Results: Super Sorgo exhibited the highest fresh forage and dry matter (DM) yield, with only Silo Miel achieving a comparable DM yield. Silo Master and Gigante Verde produced DM yields similar to both Silo Miel and corn. Optimal fermentation profiles characterized by elevated lactic acid concentrations and lower pH were observed in corn and conventional sorghum varieties. Conversely, BMR sorghum displayed the least favorable fermentation parameters. Regarding nutritional quality, Super Sorgo and Silo Master silages had the lowest crude protein (CP) contents. Neutral detergent fiber (NDF) levels were highest in corn and comparable in Silo Miel, Silo Master, and Gigante Verde. Corn silage demonstrated the greatest digestibility of both DM and NDF, a trait matched only by Silo Miel, Silo Master, and Gigante Verde.

Limitations/Implications: No limitations were identified in this study.

Findings/Conclusions: Super Sorgo and Silo Miel are recommended for systems aiming to maximize forage yield. Meanwhile, Silo Miel, Silo Master, Gigante Verde, and corn are preferable when targeting high nutritional quality forage in dairy and/or forage production systems under the prevailing climate and management conditions suitable for sorghum cultivation.

Keywords: *Sorghum bicolor* (L.) Moench, fermentation, nutrition.



INTRODUCTION

Sorghum originates from Africa and is globally recognized as a multipurpose crop, utilized for food, forage, fiber, and fuel production (Zheng *et al.*, 2011). It ranks as the fifth most important cereal crop worldwide, following wheat (*Triticum aestivum*), rice (*Oryza sativa* L.), maize (*Zea mays* L.), and barley (*Hordeum vulgare* L.) (FAO, 2022). As a C4 plant, sorghum exhibits high tolerance to water stress (Jahanzada *et al.*, 2013) and elevated temperatures (Peacock, 1982). Additionally, it shows moderate tolerance to soil salinity (Saber *et al.*, 2011) and possesses high photosynthetic efficiency, allowing it to thrive in arid and semi-arid regions (Zhang *et al.*, 2018). Under such conditions, sorghum can yield more forage than forage maize (Singh & Singh, 1995; Pedersen, 1996). However, conventional sorghum varieties often have a high lignin content (up to 9.1% of DM), which is associated with silages of low fiber digestibility. This negatively impacts feed intake and milk production in dairy cows (Grant *et al.*, 1995; Miron *et al.*, 2007). Commercial forage sorghum varieties are generally characterized by tall stature, low panicle percentage, a physiological cycle longer than 100 days, and high dry matter yield per hectare (Núñez *et al.*, 2011). However, these traits can vary significantly among varieties, as each is genetically developed for different end uses. Single-cut or conventional sorghums are tall, high-yielding, and moderately nutritious, commonly used for animal feed and industrial applications (Gnansounou *et al.*, 2005; Kumar *et al.*, 2010). Super sorghums, primarily used for biofuel production, exhibit very tall growth, with growth rates ranging from 3.9 to 6.4 cm/day and high concentrations of fermentable sugars (up to 20.1 °Brix), especially in the stem (García *et al.*, 2016). These characteristics make super sorghum highly suitable for ethanol production, particularly due to its lower water requirement compared to maize and sugarcane (García *et al.*, 2016; Montes *et al.*, 2010). Brown midrib (BMR) sorghums, though lower in biomass yield due to shorter plant height, provide higher forage quality, offering fiber digestibility rates of 62.4% compared to 56.4% in conventional sorghums (Oliver *et al.*, 2004). Grain sorghums are also used for silage in livestock systems; however, their short stature results in lower biomass yields, albeit with superior nutritional quality and fiber digestibility due to a favorable leaf-to-stem ratio (Calderón-Sánchez *et al.*, 2011). In regions characterized by high temperatures, water scarcity, and limited agronomic inputs, sorghum emerges as a viable alternative to forage maize. Unlike maize, sorghum does not suffer significant yield losses when temperatures exceed 30 °C (Bernardes *et al.*, 2018). Furthermore, sorghum uses 30% less water (Getachew *et al.*, 2016), responds more efficiently to nitrogen application (Holman *et al.*, 2024), and requires fewer herbicides (Assefa *et al.*, 2013). In a semi-arid region comparable to the current study site, sorghum outperformed forage maize in fresh forage yield (0.43 t/ha *vs.* 0.35 t/ha) and water use efficiency (105 kg/ha/mm *vs.* 79 kg/ha/mm) at 105 days post-sowing under limited irrigation conditions (Bhattarai *et al.*, 2020). In fact, under a projected increase in annual mean temperature (1 to 4 °C), sorghum forage yield increased by 0.53 t/ha of DM for each 1 °C increment, whereas forage maize experienced an 11% yield reduction between 30 and 38 °C (Druille *et al.*, 2020; Reyes-González *et al.*, 2024). Moreover, silages produced in warm climates often suffer from reduced fermentative quality and nutritional value (Bernardes *et al.*, 2018).

The aim of this study was to evaluate forage production, fermentation quality, and the nutritional value of silage from five commercial sorghum varieties in comparison with forage maize.

MATERIALS AND METHODS

Experimental site and treatments

The experiment was established during the spring 2020 production cycle at the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) research station in Matamoros, Coahuila, Mexico. The experimental site is located at 25° 53' 31" N latitude and 103° 24' 11" W longitude, at an altitude of 1,116 m above sea level. The soil texture at the site is silty-clayey, with a bulk density of 1.07 g cm⁻³, an organic matter content of 1.5 % and a pH of 8.3. The effect of five commercial forage sorghum varieties Silo Miel (control), Silo Máster, Gigante Verde, Agri 7401 (BMR) and Super Sorgo SE45 was evaluated, alongside the forage maize hybrid SB-302, on forage production, silage fermentation and nutritional value.

Forage production measurements

Forage production was assessed by fresh forage and dry matter (DM) yields; in addition, plant height and proportions of leaves, stems and panicle (for sorghum) or ear (for maize) were recorded. Silage fermentation parameters included pH, ammoniacal nitrogen and percentages of lactic acid, acetic acid, propionic acid and butyric acid. For nutritional value of the silage, analyses included: DM, crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), lignin, ash, non-fibrous carbohydrates (NFC), total digestible nutrients (TDN), net energy for lactation (NE_L), *in situ* digestibilities of DM and NDF at 30 h (DMD30, NDFD30), potentially digestible NDF at 120 h (pdNDF120) and indigestible NDF at 120 h (uNDF120).

Agronomic management

Soil preparation consisted of fallow, double harrowing and leveling with a scraper. Planting occurred on 17 April 2020 in moist soil using a two-row mechanical planter (John Deere MP25) at a sowing rate of 12 kg ha⁻¹ for sorghum and a target density of 95,000 plants ha⁻¹ for maize. The experimental design was a randomized complete block with four replications. Each treatment comprised four 8.0-m-long rows with 0.76 m inter-row spacing. Average plant density achieved was 200,000 plants ha⁻¹ for sorghum and 95,000 plants ha⁻¹ for maize. Fertilization comprised 310 kg N ha⁻¹, 100 kg P₂O₅ ha⁻¹ and 0 kg K₂O ha⁻¹, estimated based on crop nitrogen requirement and yield target. All phosphorus was applied at sowing; nitrogen was split (40% at sowing, 60% before the first irrigation at 35 days after sowing (DAS)). At sowing also applied: 8 kg K₂O ha⁻¹, 10 kg S ha⁻¹; before first irrigation: 18 kg Ca ha⁻¹ and 12 kg MgO ha⁻¹. Fertilisers used: Yara Mila Star[®] and Yara Bela Nitromag[®] (Yara, Guadalajara, Jalisco). Five irrigations were applied, including a pre-sowing irrigation. The four supplementary irrigations occurred at 37, 59, 80 and 100 DAS, according to the irrigation calendar commonly used for sorghum and forage maize in the Comarca Lagunera Irrigation District. Surface irrigation

with well water was employed. Pest control: at 25 and 46 DAS, applications of chlorpyrifos (Lorsban 480 EM[®], BASF Inc., Germany) at 0.75 L ha⁻¹ for control of fall armyworm (*Spodoptera frugiperda*); at 50 and 83 DAS, applications for control of yellow sugarcane aphid (*Melanaphis sacchari*) using imidacloprid + betacyfluthrin (Muralla Max[®], Bayer, Mexico) at 0.25 mL ha⁻¹ and sulfoxaflor (Toretto Isoclast[®] Active, Corteva Agrosiences, Guadalajara) at 100 mL ha⁻¹. Weed control was performed manually.

Harvest and forage yield determination

The crop was harvested on 17 August 2020 at 123 DAS when sorghum reached the milk-dough grain stage and maize at two-thirds milk-line stage, after accumulation of 2,145 heat units. Heat units were calculated as $(T_{max} + T_{min})/2 - \text{base } 10\text{ }^{\circ}\text{C}$ (Osuna-Ceja & Martínez-Gamiño, 2017). The two central rows served as the useful plot by excluding 1 m at each end; six metres of length per treatment (9.12 m²) were harvested. Fresh forage from each plot was weighed to estimate fresh yield. Representative samples were obtained to determine percent DM by drying in a forced-air oven at 65 °C to constant weight. DM yield per hectare was calculated by multiplying fresh yield by the DM content of each plot. At harvest, plant height and aerial biomass organ distribution were measured. Percentages of panicle, leaves and stems in sorghum, and ear, leaves and stems in maize were estimated from representative samples of five plants randomly selected from each plot. From all plants harvested per plot, 15 plants were further selected, chopped to theoretical particle size of 3.5-12 mm using a mill (Model JF5; Terramark, JF Máquinas Agrícolas). From the chopped fresh forage of each plot, three subsamples of 300 g each were taken, dried at 65 °C until constant weight to determine DM content at ensiling.

Silage preparation

The forage of each variety was packed in mini-silos constructed from PVC tubes (10.5 cm diameter × 18 cm length) sealed at both ends with matching end-caps (Solórzano *et al.*, 2016). A 2.78 mm-diameter drainage hole was drilled in the centre of the lower cap for effluent release during compaction. For each treatment, forage was packed at a density of 261 kg m⁻³ DM (Sucu E. *et al.*, 2016). The amount of forage per mini-silo was calculated using the measured DM content (29.67 ± 0.42%) and the silo volume. Compaction was performed using a manual press consisting of a steel arm and a 4-ton hydraulic jack that pressed the mini-silo. After sealing with adhesive tape, the mini-silos were transported to the laboratory and fermented for 90 days. The experimental design for silages was a randomized complete block with four replications.

Silage fermentation and nutritional value analysis

After the fermentation period, the top 5 cm of each mini-silo was discarded. Then 20 g of fresh silage was mixed with 200 mL of deionised distilled water and homogenised in a blender for 30 s. The mixture was filtered through muslin cloth and 10 mL of filtrate was centrifuged at 4,000 rpm for 15 min. From the supernatant, 5 mL were transferred into 15 mL amber vials (Supelco[®]) with 1 mL (250 µL mL⁻¹) of metaphosphoric acid and frozen until analysis. Upon thawing, samples were filtered through 0.45 µm cellulose

acetate membranes and volatile fatty acids (VFAs: lactic, acetic, propionic, butyric acids) were identified and quantified by high-performance liquid chromatography (HPLC) using an Agilent 1200 system equipped with diode-array detector and quaternary pump. Separation occurred on an Aminex HPX-87H (300 mm×7.8 mm) ion-exclusion column, detection at 210 nm. Mobile phase was 5 mM sulfuric acid at 0.6 mL min⁻¹. VFAs were quantified using certified standards (lactic, acetic, propionic, butyric acids) and calibration curves ($R^2 \geq 0.99$) (Canale *et al.*, 1984). Additionally, a separate 20 g silage sample was mixed with 80 mL deionised water, shaken for 4 h, filtered (Whatman[®] #1), and the filtrate centrifuged at 2,500 rpm for 15 min. The supernatant underwent ammoniacal-nitrogen analysis via Kjeldahl method (AOAC, 1984). For nutritional value analysis, 350 g of fermented silage were dried in aluminium trays (32×26×6 cm) at 65 °C for 72 h in a forced-air oven (SHEL-LAB FX28-2) and then ground to pass a 1 mm Wiley mill (Arthur T. Thomas, Swedesboro, NJ). Total nitrogen was determined by dry-combustion Dumas method (Leco FP-528), and CP calculated as N×6.25. Fibre analysis: sequentially NDF in 0.5 g sample placed in 25 µm filter bags (F57, Ankom Tech.), using thermo-stable α-amylase and sodium sulfite in an A200 fibre analyser. After drying and weighing, ADF with CTAB and H₂SO₄ was determined, then lignin using 72% H₂SO₄ in the same bags. Ash content was determined by combusting 2.0 g dry sample in a muffled furnace at 550 °C for 6 h. Non-fibrous carbohydrates (NFC) were calculated as:

$$NFC(\%) = 100 - (\%CP + \%NDF + \%ash + \%EE)$$

assuming EE (ether extract) of 2.8 % for all samples. Total digestible nutrients (TDN) and net energy for lactation (NE_L) were estimated using the NRC model (equations 2-5 and 2-11, respectively) based on the chemical-composition results.

For digestibility analysis, 4.5 g of dried sample were enclosed in 10×20 cm filter bags (50 µm, R1020, Ankom Tech.) and incubated in duplicate for 30 h and 120 h in the rumen fistula sac of two cannulated cows (Zapotlanejo, Jalisco). Samples for pdNDF120 and uNDF120 were incubated for 120 h, while NDFD30 samples were added 30 h before the end of the 120-h incubation. All bags were removed simultaneously, plunged for 10 min in cold water (4 °C), rinsed until clear, drained, and dried in a forced-air oven at 55 °C for 48 h. Digestible DM was calculated by weight difference. Approximately 0.5 g of residual sample was placed in an F57 bag for residual NDF and calculation of pdNDF120 and NDFD30.

Statistical analysis

Data were analysed using SAS version 9.3 (SAS Institute, 2011). ANOVA was conducted using a randomized complete block design with six treatments and four replications for forage yield, silage fermentation and nutritional value variables. When significant differences ($P < 0.05$) were detected, Fisher's protected least significant difference (LSD) test was applied to compare treatment means at the same significance level.

RESULTS AND DISCUSSION

Climatic conditions

Precipitation and ambient temperature during the crop development period are presented in Figure 1. Cumulative precipitation throughout the cycle was only 5.4 mm. Maximum daily temperatures ranged from 23 to 39 °C, while minimum temperatures fluctuated between 15 and 24 °C. The highest temperatures, which exceeded the optimal growth range for sorghum (6-37.7 °C) (Peacock, 1982), were recorded between 41 and 52 days after sowing (DAS).

Daily precipitation and ambient temperature conditions during the evaluation cycle of sorghum and forage maize hybrids at the La Laguna Experimental Station (INIFAP) are shown in Figure 1. Cumulative rainfall during the crop cycle was 5.4 mm. Maximum temperatures ranged from 23 °C to 39 °C, while minimum temperatures varied from 15 °C to 24 °C. The highest temperatures, which exceeded the optimal growth range for sorghum (6-37.7 °C) (Peacock, 1982), occurred between 41 and 52 days after sowing (DAS).

Days to harvest and plant height

Significant differences were found in days to harvest and plant height among the evaluated sorghum and maize varieties (Table 1). The Gigante Verde sorghum variety and maize reached harvest at 115 days, while the remaining sorghum varieties matured at 122 days ($P < 0.0001$). Super Sorgo was the tallest variety, exceeding Silo Miel and Gigante Verde by 0.82 m and BMR sorghum and maize by 1.93 m ($P < 0.0001$). Gigante Verde was the only variety comparable in height to Super Sorgo. While Super Sorgo is the result of natural crosses developed to reach heights of up to 5 m at a growth rate of 6.4 cm per day (García *et al.*, 2016), BMR sorghum is phenotypically shorter, approximately 1.86 m tall, designed for improved forage nutritive value (Srinivasa *et al.*, 2012).

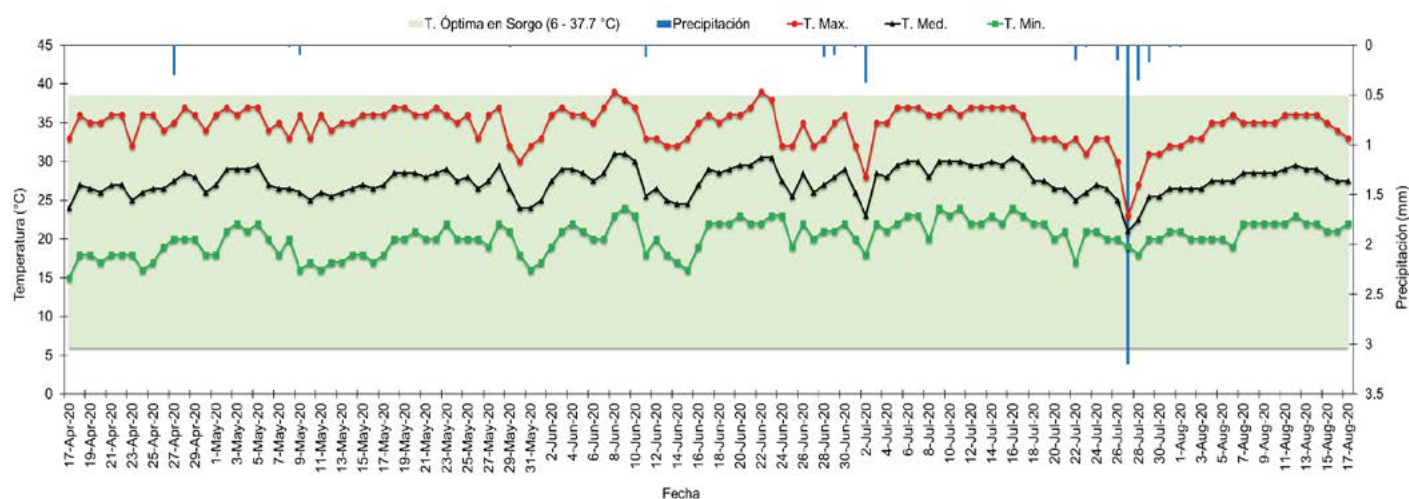


Figure 1. Daily weather conditions during the evaluation cycle of sorghum and forage maize hybrids at the La Laguna Experimental Station (INIFAP).

Forage production

Fresh and dry matter (DM) forage yields are presented in Table 1. The highest fresh forage yield was recorded in Super Sorgo with 115 t ha^{-1} , significantly exceeding that of all other sorghum varieties and maize ($P < 0.0001$). Likewise, Super Sorgo outperformed Silo Máster and Gigante Verde by an average of 8 t ha^{-1} and BMR sorghum and maize by 11.8 t ha^{-1} ($P < 0.0001$). In terms of DM yield, Super Sorgo was matched only by Silo Miel, which showed similar yields to Silo Máster, Gigante Verde, and maize. García *et al.* (2016) reported even higher fresh (167 t ha^{-1}) and DM (23.46 t ha^{-1}) yields in eight Super Sorgo varieties compared to forage maize (65 t ha^{-1} fresh, 23.46 t ha^{-1} DM). This is attributed to the fast growth and high biomass accumulation capacity of sweet sorghum, making it a valuable biomass source for forage and bioethanol production (Kumar *et al.*, 2010). Similar to our findings, Marsalis *et al.* (2010) reported higher DM yields in conventional sorghum and forage maize varieties (24.4 t ha^{-1}) than in BMR sorghum (21.1 t ha^{-1}).

Dry matter distribution in plant organs

Dry matter distribution among aerial plant parts showed that BMR sorghum accumulated a higher proportion of DM in leaves (32.52%) and panicles (29.94%) compared to other sorghum varieties and maize ($P < 0.0001$; Table 1). Conversely, Super Sorgo allocated the highest DM proportion to stems (72%), surpassing all other sorghum varieties and maize ($P < 0.0001$). These differences in the proportion of leaves, stems, and panicles may influence both yield and nutritive composition of the forage produced. It has been observed that the leaf:stem:panicle ratio in forage sorghum varies significantly throughout the growth cycle, with an increasing proportion of DM in the stem as the crop develops. During the first 52 days of growth, leaves represented a greater proportion (44.7%) than stems (23.4%). By day 57, the leaf-to-stem ratio equalized, while from day 80 to 122, stems predominated (54.4-60.4%) over leaves (26.4-13.9%) and panicles (15.1%).

Table 1. Days to harvest, plant height, fresh and dry matter (DM) forage yields, and DM distribution among aerial organs in sorghum and forage maize varieties.

Variable	Super Sorgo	Silo Miel	Silo Máster	Gigante Verde	BMR Sorghum	Maize	SE	P-value
Days to harvest	122	122	122	115	122	115	–	–
Plant height (m)	4.12 ^a	3.34 ^b	3.47 ^b	3.73 ^{ab}	1.90 ^c	2.49 ^c	0.11	<0.0001
Fresh forage yield (t ha^{-1})	115.9 ^a	89.78 ^b	88.76 ^b	85.76 ^b	59.02 ^c	51.15 ^c	4.96	<0.0001
Dry matter at harvest (%)	24.71 ^b	26.22 ^b	23.54 ^b	23.42 ^b	25.71 ^b	35.62 ^a	0.74	<0.0001
Dry matter yield (t ha^{-1})	28.56 ^a	23.48 ^{ab}	20.92 ^{bc}	20.06 ^b	15.24 ^c	18.23 ^{bc}	1.33	<0.0001
Leaves (% DM)	15.65 ^c	22.51 ^b	23.73 ^b	23.07 ^b	32.52 ^a	19.29 ^{bc}	1.14	<0.0001
Stems (% DM)	72.00 ^a	65.20 ^b	62.70 ^b	63.11 ^b	37.54 ^c	26.23 ^d	1.49	<0.0001
Panicle/Ear (% DM)	12.35 ^c	12.30 ^c	13.57 ^c	13.82 ^c	29.94 ^b	54.47 ^a	1.66	<0.0001

^{abc} Means followed by different letters within a row are significantly different at the indicated probability level according to Fisher's protected LSD test. SE: Standard error. Super Sorgo SE45, BMR sorghum Agri 7401, and maize SB-302.

(Amador & Boschini, 2000). This final DM distribution among aerial organs closely resembles that observed in conventional sorghums in the present study.

Silage fermentation

Fermentation parameters of the silages are presented in Table 2. Maize silage exhibited the highest dry matter (DM) content, while the silage from the Gigante Verde sorghum variety had the lowest ($P < 0.0001$). The silages from conventional sorghums (Silo Miel, Silo Máster, and Gigante Verde) and Super Sorgo displayed pH values similar to maize, with the lowest values ranging from 3.73 to 3.96. In contrast, the BMR sorghum silage had the highest pH (4.39). These pH values were clearly influenced by lactic acid production in the silages; conventional sorghums and Super Sorgo produced the highest lactic acid concentrations (2.94-3.35%), similar to those observed in maize. BMR silage exhibited the lowest lactic acid content, which may be attributed to a reduced availability of water-soluble carbohydrates (WSC) in BMR sorghum, limiting lactic acid bacteria (LAB) activity and resulting in insufficient lactic acid production to lower pH (Kung *et al.*, 2018). Thomas *et al.* (2013) found that lactic acid concentration and pH in BMR sorghum silage significantly improved with microbial inoculants containing *Lactobacillus buchneri* and *Lactobacillus plantarum*, in comparison to conventional sorghum silage. Comparative studies between maize and sorghum silages show that maize silage achieves better pH (3.92) and lactic acid levels (7.32%) than sorghum silage (pH=4.24, 6.75% lactic acid) (Brouwer *et al.*, 1991). These differences may be explained by the higher crude protein (CP) content in sorghum, which increases buffering capacity in the silo (Ratnaningtyas *et al.*, 2023), as well as higher concentrations of water-soluble carbohydrates and starch in maize compared to sorghum (Brouwer *et al.*, 1991; Ratnaningtyas *et al.*, 2023). The highest acetic acid concentration was observed in BMR sorghum silage (4.82%), a value only matched by Silo Máster (3.23%) and Gigante Verde (3.35%) sorghum silages ($P = 0.0108$). Elevated levels of acetic acid have been associated with silages having excessively high moisture content (<25% DM)

Table 2. Fermentation parameters of silages from various forage sorghum genotypes and maize.

Parameter	Super Sorgo	Silo Miel	Silo Máster	Gigante Verde	BMR Sorghum	Maize	SE	P-value
Dry matter (% of silage)	28.48 ^{bc}	29.85 ^b	28.59 ^{bc}	25.30 ^c	28.30 ^{bc}	33.81 ^a	0.81	<0.0001
Silage pH	3.73 ^b	3.81 ^b	3.82 ^b	3.81 ^b	4.39 ^a	3.96 ^b	0.056	<0.0001
Ammoniacal N (% of total N)	11.68	11.56	11.49	8.98	9.64	9.36	0.90	0.1209
Lactic acid (% of DM)	5.77 ^a	6.59 ^a	7.15 ^a	6.67 ^a	1.81 ^b	6.59 ^a	0.60	<0.0001
Acetic acid (% of DM)	2.73 ^b	2.94 ^b	3.23 ^{ab}	3.35 ^{ab}	4.82 ^a	3.15 ^b	0.37	0.0108
Propionic acid (% of DM)	0.00	0.00	0.21	0.00	0.08	0.00	0.087	0.4756
Butyric acid (% of DM)	0.00	0.00	0.00	0.00	0.00	0.00	0.09	–
Total VFAs	8.50 ^{bc}	9.53 ^{ab}	10.58 ^a	10.02 ^{ab}	6.71 ^c	8.76 ^{ab}	0.44	<0.0001
Lactic acid (% of total VFAs)	68.05 ^a	69.18 ^a	67.77 ^a	66.51 ^a	22.93 ^b	63.89 ^a	6.48	0.0006
Lactic acid / Acetic acid ratio	2.23 ^a	2.29 ^a	2.25	2.02 ^a	0.59 ^b	1.82 ^{ab}	0.29	0.0055

^{abc} Means followed by different letters within a row are statistically different at the indicated probability level according to Fisher's protected LSD test. SE=standard error. Super Sorgo SE45, BMR sorghum Agri 7401, and maize SB-302.

(Kung & Shaver, 2001). However, all silages in this study had DM levels above 25%. The total volatile fatty acid (VFA) concentration was lowest in BMR sorghum silage, a value statistically similar to that of Super Sorgo silage ($P < 0.0001$).

Nutritional value of silage

Table 3 presents the nutritional value of the evaluated silages. Crude protein (CP) content varied among treatments, with the lowest concentrations observed in Super Sorgo and Silo Máster silages (5.05-5.74%). In contrast, the remaining sorghum varieties had CP values comparable to maize silage (7.9%). Regarding fiber content, neutral detergent fiber (NDF) values ranged from 41.74% to 47.39% and acid detergent fiber (ADF) from 31.50% to 34.32% across sorghum silages, with no significant differences among them. These findings differ from those of García *et al.* (2016), who reported that BMR sorghum had lower NDF and fewer indigestible components compared to conventional sorghums (Bean *et al.*, 2009). Compared to maize silage, NDF content in Silo Miel, Silo Máster, and Gigante Verde sorghum silages was similar, while Super Sorgo and BMR silages showed lower values. However, for ADF, the values in Silo Miel, Silo Máster, and BMR

Table 3. Nutritional value of silages from different forage sorghum and maize hybrids.

Parameter	Super Sorgo	Silo Miel	Silo Máster	Gigante Verde	BMR Sorghum	Maize	SE	P-value
Crude protein (CP, % of DM)	5.05	8.95	5.74	6.87	8.26	7.90	0.30	<0.0001
Neutral detergent fiber (NDF, % of DM)	41.74	47.24	45.59	47.39	41.74	51.43	1.95	0.0189
Acid detergent fiber (ADF, % of DM)	35.59	31.55	31.50	34.32	32.65	27.53	1.41	0.0140
Lignin (% of DM)	5.69	5.40	6.15	6.24	5.30	4.14	0.84	0.5305
Ash (% of DM)	3.14	5.93	6.93	4.95	8.43	4.59	0.52	<0.0001
Lignified NDF (LNDF)	13.61	11.52	13.43	13.57	12.79	8.00	1.97	0.3121
Non-fibrous carbohydrates (NFC, % of DM)	47.14	38.00	38.85	37.91	38.69	33.21	1.66	0.0006
Total digestible nutrients (TDN, % of DM)	58.36	52.45	57.41	55.53	55.14	61.21	1.93	0.0738
Net energy for lactation (NE _L , Mcal/kg)	1.27	1.10	1.25	1.20	1.21	1.38	0.058	0.0463
DM digestibility at 30h (DMD30, % of DM)	46.86	50.54	49.21	45.29	45.14	55.80	1.80	0.0057
pdNDF at 120h (% of NDF)	57.79	60.87	60.50	57.73	66.43	68.59	1.11	<0.0001
uNDF at 120h (% of NDF)	42.21	39.12	39.49	42.27	33.57	31.41	1.11	<0.0001
NDF digestibility at 30h (NDFD30, % NDF)	16.55	33.38	27.76	32.39	22.22	32.57	2.22	0.0001

^{abc} Means within each row followed by different letters are statistically different at the indicated probability level. SE=standard error. CP=crude protein; NDF=neutral detergent fiber; ADF=acid detergent fiber; LNDF=lignified NDF calculated as $100 \times (\% \text{ Lignin} / \% \text{ NDF})$; NFC=non-fibrous carbohydrates; TDN=total digestible nutrients; NE_L=net energy for lactation. DMD30=*in situ* dry matter digestibility at 30 h; pdNDF120=potentially digestible NDF at 120 h; uNDF120=undigestible NDF at 120 h; NDFD30=*in situ* NDF digestibility at 30 h. ¹Chemical composition expressed as a percentage of dry matter (DM), unless otherwise indicated. Super Sorgo SE45, BMR sorghum Agri 7401, and maize SB-302.

sorghum were similar to maize, while Super Sorgo and Gigante Verde had higher ADF levels, indicating potentially lower nutritive value (García *et al.*, 2016). Non-fibrous carbohydrates (NFC) content was highest in Super Sorgo silage compared to all others ($P=0.0006$), while the remaining silages had similar NFC concentrations. In terms of energy, Silo Miel silage showed a net energy for lactation (NE_L) value lower than maize, while the other sorghum silages had NE_L values statistically similar to that of maize. Similar findings were reported by García *et al.* (2016), who observed no differences in NE_L between maize silage (1.35 Mcal/kg) and two Super Sorgo varieties (1.35 Mcal/kg). According to Grant & Stock (1994), sorghum silage contains only 80-90% of the energy content of maize silage per unit of DM, largely due to a lower grain-to-forage ratio in sorghum and a significant portion of undigested grain in the silage. Significant differences were observed in DM and NDF digestibility among the silages (Table 3). Maize silage had 10% higher DM digestibility compared to Super Sorgo, Gigante Verde, and BMR sorghum silages ($P=0.005$). NDF digestibility was also highest in maize silage (32.57%) and was only matched by Silo Miel (33.38%), Silo Máster (27.76%), and Gigante Verde (32.39%) silages. The lowest NDF digestibility was recorded in BMR and Super Sorgo silages. The higher NDF digestibility in maize is likely due to a greater proportion of potentially digestible NDF (pdNDF) ($P<0.0001$) and lower undigestible NDF (uNDF) ($P<0.0001$) compared to conventional sorghum silages. Interestingly, BMR silage had pdNDF and uNDF values similar to maize, yet showed no improvements in DM and NDF digestibility.

In another study, Sánchez-Duarte *et al.* (2019) reported lower NDF digestibility in conventional sorghum silage (50.8%) compared to BMR sorghum (58.2%). They also found higher NDF digestibility in BMR sorghum silage (55.1%) than in conventional maize silage (53.2%). It is possible that the irrigation schedule applied in this study, which was designed for sorghum, may have negatively affected fiber digestibility in maize, which reached only 32.39% (Table 3) well below the 57% NDF digestibility reported for maize in the same region under shorter irrigation intervals (Granados *et al.*, 2023).

CONCLUSIONS

Forage production indicated that Super Sorgo had a higher fresh forage yield than the other sorghum varieties and maize, producing 8 to 11 t ha⁻¹ more dry matter (DM) than the other sorghums and maize. The Silo Miel variety matched Super Sorgo in DM production. Silage fermentation showed better fermentative parameters in all conventional sorghums and maize compared to BMR sorghum. Nutritionally, maize had the highest NDF digestibility, while Super Sorgo had the lowest. Only the Silo Miel, Silo Master, and Gigante Verde sorghum varieties matched the NDF digestibility of maize, with no positive effects observed in BMR sorghum. Therefore, Super Sorgo and Silo Miel varieties should be considered when the objective is to maximize forage quantity, while Silo Miel, Silo Master, Gigante Verde, and maize are suitable options when the goal is to produce nutritionally high-quality forage in milk and/or forage production systems under climatic and agronomic conditions suited for forage sorghum.

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