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Effects of Row Spacing and Tropical Grass Intercropping on Biomass Sorghum Yield and Silage Quality

Giuliano Reis Pereira Muglia [1,*], Marco Antonio Previdelli Orrico Junior [1], Isabele Paola de Oliveira Amaral [1], Marciana Retore [2], Gessí Ceccon [2], Ana Carolina Amorim Orrico [1], Pedro Henrique Felipe da Silva [1] and Yara América da Silva [1]

1 College of Agricultural Science, Federal University of Grande Dourados, Dourados 79804-970, MS, Brazil; marcojunior@ufgd.edu.br (M.A.P.O.J.); isabelep.oliveira@gmail.com (I.P.d.O.A.); anaorrico@ufgd.edu.br (A.C.A.O.); pedro.dasilva@colaborador.embrapa.br (P.H.F.d.S.); yaraamerica603@gmail.com (Y.A.d.S.)
2 Brazilian Agricultural Research Corporation, Embrapa Agropecuária Oeste, Dourados 79804-970, MS, Brazil; marciana.retore@embrapa.br (M.R.); gessi.ceccon@embrapa.br (G.C.)
* Correspondence: gmuglia12@gmail.com; Tel.: +55-67-999488907

Abstract

This study aimed to determine the optimal combination of forage grass and row spacing to maximize the balance between sorghum silage yield and quality in a simultaneous sowing system for integrated crop-livestock production. The experiment evaluated three cropping systems: biomass sorghum (*Sorghum bicolor* (L.) Moench) in monoculture, and intercropped with *Urochloa brizantha* cv. Marandu and *Megathyrsus maximus* cv. BRS Zuri. These systems were tested under two row spacings: 45 cm and 90 cm. The field trial was conducted in Vicentina, Mato Grosso do Sul State, Brazil, using a randomized complete block design in a 3 × 2 factorial arrangement with four replications. Dry matter production, fermentative parameters, and chemical composition were measured. The 45 cm spacing provided higher productivity (23.1 t/ha of TDMY), while the intercropping with Zuri grass showed lower levels of NDF (73.46%) and ADF (49.61%), indicating better nutritional quality. The silages exhibited ideal pH (4.0–4.1) and low levels of butyric acid (<0.33%), with higher total digestible nutrients (TDN) (54.33%) at the 90 cm spacing. The Sorghum + Zuri (ZS) intercropping at the narrower spacing (45 cm) is viable for quality silage production, showing a better balance between overall chemical quality and biomass production.

Keywords: crop-livestock integration; row spacing; *Sorghum bicolor*; silage quality; tropical forages

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1. Introduction

Brazil has approximately 180 million hectares of pastureland, representing about 21.12% of the national territory [1]. However, nearly 50% of these areas exhibit some degree of degradation [1], which compromises system productivity and, consequently, the efficiency of animal production, given that pastures are the foundation of the national livestock industry [2].

In this context, integrated systems, especially crop-livestock integration (CLI), have emerged as a strategic alternative for rehabilitating degraded areas. This approach promotes sustainable intensification, enhances soil carbon sequestration, reduces pest and disease pressure, and increases farm productivity and profitability [3]. The inclusion of annual crops like corn and sorghum in CLI systems enables a faster economic return, either through grain or silage production, thereby offsetting pasture renewal costs even before its utilization phase begins [4–7].

The implementation of CLI for rehabilitating pastures in the Cerrado often relies on the intercropping of annual crops with perennial forage species, notably those from the *Megathyrsus* spp. and *Urochloa* spp. genera. Sorghum has emerged as a key component in these systems across Central-West Brazil, owing to its attributes of drought tolerance, commendable nutritional quality, high dry matter output, and ratooning potential. These traits are highly desirable for production environments characterized by intermediate soil fertility and erratic rainfall distribution [8,9].

Conventional practice for grain sorghum intercropped with forage grasses uses a staggered planting schedule, sowing the forage 7 to 14 days after the sorghum to reduce early competition [10,11]. While effective, this requires an extra field operation, increasing costs. Biomass sorghum hybrids, however, display a more robust growth habit, increased stature, and superior competitive ability compared to their grain-type counterparts. This enhanced vigor provides a physiological basis for a key management innovation: simultaneous sowing with forage grasses.

Previous studies on other crops have suggested that such practice can reduce operational complexity and lower costs by eliminating the need for a separate sowing pass [12,13]. Adopting simultaneous sowing with biomass sorghum could therefore accelerate pasture establishment after harvest, thereby boosting the productivity and sustainability of integrated systems. However, the impact of this practice on both sorghum performance and forage establishment remain inadequately documented for biomass sorghum in the Cerrado biome, particularly regarding the specific choice of forage grass partner.

The selection of *Urochloa brizantha* cv. Marandu and *Megathyrsus maximus* cv. BRS Zuri for this study was based on their distinct growth habits and prevalence in Brazilian pastures. Marandu grass is widely adopted due to its adaptability and good forage quality, while Zuri grass is recognized for its high dry matter yield and nutritional value [14,15]. Preliminary field observations and studies with other crops [16,17] indicate their potential for successful intercropping, but a systematic evaluation of their compatibility with biomass sorghum under simultaneous sowing is lacking.

The economic impetus for this research is clear. Conventional staggered sowing incurs significant additional costs from extra labor, machinery use, and fuel. While specific data for sorghum is scarce, analogous operations in other cropping systems incur measurable costs, highlighting the substantial potential savings of a successful simultaneous sowing system [18].

Therefore, to address the core question of whether simultaneous sowing of biomass sorghum with tropical forages is a viable strategy for integrated systems, this study tested two central hypotheses. First, that simultaneous sowing with either Marandu or Zuri grass would maintain the biomass production and fermentative quality of the silage compared to sorghum monoculture. Second, that a narrower row spacing (45 cm) would enhance light capture and biomass accumulation, but we also anticipated potential trade-offs, such as the 90 cm spacing potentially favoring the intercropped grass and influencing specific quality parameters like fiber content and digestibility.

Consequently, this study aimed to determine the optimal combination of forage grass and row spacing to maximize the balance between sorghum silage yield and quality, and the subsequent pasture establishment in a simultaneous sowing system.

2. Materials and Methods

2.1. Site Characterization

The experiment was conducted on a farm (22°26′41″ S, 54°21′10″ W) located in the municipality of Vicentina, Mato Grosso do Sul State, Brazil. According to the Köppen classification, the regional climate is type Cwa (humid subtropical with a rainy summer) [19]. The soil is classified as a eutrophic Red-Yellow Latosol (Oxisol) with a sandy texture [20]. Monthly rainfall and temperature data (minimum, maximum, and average) recorded throughout the experimental period are presented in Figure 1.

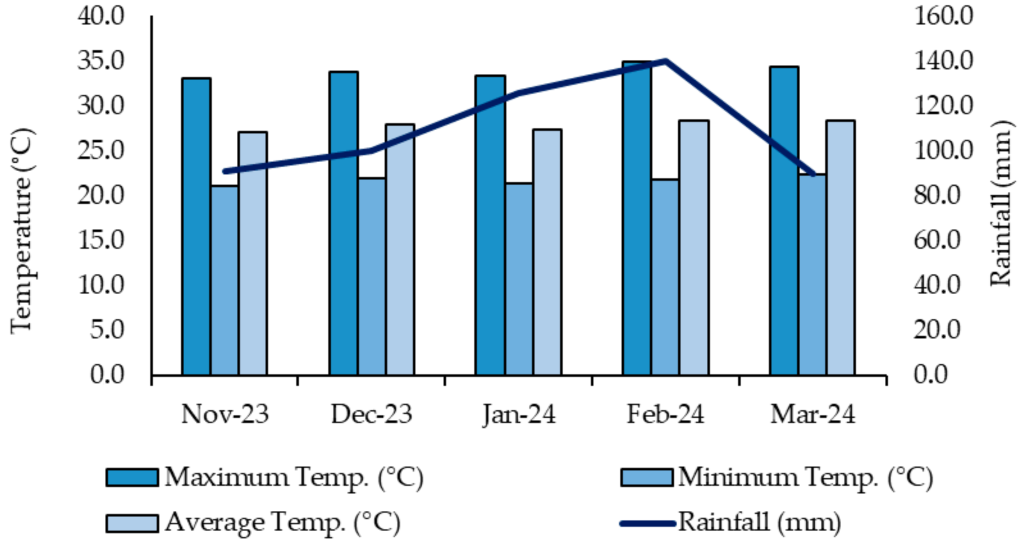

Figure 1. Monthly rainfall and temperature (maximum, average, and minimum) during the experimental period in Vicentina, Mato Grosso do Sul State, Brazil. Source: Guia Clima—Embrapa.

2.2. Soil Sampling, Fertilization, and Cultural Practices

In September 2023, soil samples were collected from the 0–20 cm layer for the evaluation of physical and chemical attributes. All physical and chemical soil analyses were carried out according to the methodology described by [21]. The soil attributes are shown in Table 1.

Table 1. Physicochemical Characterization of the Experimental Soil (0–20 cm depth).

Attributes	Value	Unit
Chemical Properties		
pH	5.0	-
P	3.8	mg/L
Cations		
Ca	18.9	mmolc/L
Mg	9.0	mmolc/L
K	1.7	mmolc/L
H + Al (Potential Acidity)	16.0	mmolc/L
Al	0.0	mmolc/L
Calculated Values		
Sum of Bases	29.6	mmolc/L
Cation Exchange Capacity (CEC) at pH 7.0	45.6	mmolc/L
Effective CEC	29.6	mmolc/L
Saturation		
Aluminum Saturation	0.00	%

Table 1. *Cont.*

Attributes	Value	Unit
Base Saturation	64.91	%
Micronutrients		
Cu	0.038	mmol/L
Fe	0.399	mmol/L
Mn	1.285	mmol/L
Zn	0.028	mmol/L
Physical Properties		
Sand	768	g/kg
Clay	182	g/kg
Silt	50	g/kg
Organic Matter	15.49	g/kg

A basal fertilizer application of 300 kg/ha of the formulation 08-20-20 (N-P-K) was applied at sowing. This was followed by a topdressing application of 150 kg/ha of nitrogen, supplied as ammonium sulfate, which was surface-applied on 26 December 2023. Both applications were based on the soil analysis report and the recommendations proposed by [22].

Insect pest control was performed by applying the insecticide Imidacloprid (neonicotinoid) + Beta-cyfluthrin (pyrethroid) + a penetrating adjuvant, primarily for the control of *Spodoptera* spp. Applications were made on 30 November 2023, 7 December 2023, and 27 December 2023. Weed control was carried out on 7 December 2023, using atrazine, applied together with the insecticide.

2.3. Experimental Design and Treatments

A randomized complete block design was employed, with treatments arranged in a 3 × 2 factorial. The factors consisted of three cropping systems: biomass sorghum monoculture (S), *Urochloa brizantha* cv. Marandu intercropped with sorghum (MS), and *Megathyrsus maximus* cv. BRS Zuri intercropped with sorghum (ZS). These systems were evaluated under two row spacings for sorghum: 45 cm and 90 cm. The experiment utilized the biomass sorghum hybrid 'Agri 002E' (Latina Seeds). Sowing was carried out on 17 November 2023, using Semeato, Passo Fundo, Brazil-SHM 15/17 seeders equipped with boxes for small seeds. The sowing depth was set at 4 cm for both sorghum and forage grasses. The target plant population was set at 100,000 sorghum plants per hectare. Each experimental plot was 12 m long, consisting of seven rows (45 cm spacing) or four rows (90 cm spacing), with four replications per treatment.

The plant population was standardized at 21 days after planting (DAP) by thinning and replanting to maintain the target density of 100,000 plants per hectare. The final established plant population across all plots ranged from 98,000 to 102,000 plants per hectare.

The experimental duration, from sowing to the harvest of sorghum for silage, was 125 days.

2.4. Biomass Yield and Chemical-Bromatological Analyses of Sorghum Silages

The evaluation of sorghum dry matter production was performed by harvesting the two central rows of each plot when the plants reached approximately 30% dry matter (DM) The DM content was monitored twice weekly, starting 90 days after planting (DAP). For each monitoring, three representative plants from the border area of each plot were collected, chopped, and sub-sampled. The sub-samples were immediately dried in a forced-air oven at 60 °C until constant weight to determine the DM content. The harvest was carried out at 125 DAP when this target was achieved. A uniform residual stubble height of 10 cm was maintained for all treatments to simulate forage harvester cutting. To evaluate grass dry matter production, samples were harvested from the same sorghum rows but were cut at ground level. The samples were weighed to determine fresh weight, and sub-samples of approximately 300 g were dried in a forced-air oven at 60 °C until constant weight to calculate dry matter yield (t/ha).

Silage was produced exclusively from sorghum plants harvested from the central rows of each plot. The forage was chopped to a theoretical particle length of 1.5 cm using a stationary chopper. After homogenization, the material was compacted into experimental PVC silos (10 cm diameter, 50 cm height, 3.8 L useful volume) at a target density of 820 kg fresh matter/m^3.

Compaction was performed manually using a wooden piston, with layers of approximately 10 cm of forage being added and compacted successively until the silo was filled. The ensiling density was verified by the total fresh mass and the known volume of the silo. To capture effluent losses, a 300 g layer of sand, separated by a mesh cloth, was placed at the bottom of each silo. The silos were then sealed with airtight plastic caps and adhesive tape and stored for 60 days in a climate-controlled room maintained at 25 ± 1 °C. This period was chosen to simulate the conditions typically observed in the region where the study was conducted, where sorghum is harvested at the end of summer and used as feed during the autumn and winter seasons [23,24].

To quantify ensiling losses, the total mass of each sealed silo was recorded at filling. After 60 days, the silos were opened [25], and the total mass was measured again. Dry matter recovery (DMR) was subsequently determined according to the formula by [26].

$$\mathrm{DMR} = 100 - \left(\frac{\mathrm{DMI} - \mathrm{DMF}}{\mathrm{DMI}} \times 100\right) \tag{1}$$

DMR = dry matter recovery (% of initial DM mass); DMI = initial DM mass (kg of DM placed in the silos); DMF = final DM mass (kg of DM removed from the silos).

2.5. Chemical-Bromatological Analyses

Following the ensiling period, the silage was thoroughly homogenized to ensure a representative sample for chemical analysis. The nutritional composition was determined via near-infrared spectroscopy (NIRS). Samples were scanned using a Foss 5000 Transport NIRS system (FOSS Analytical, Eden Prairie, MN, USA), and the spectral data were processed with WinISI 4.6.11 software using calibrations developed by the Dairy One Forage Laboratory (Ithaca, NY, USA). This method provided predictions for a wide array of parameters: dry matter (DM), ash, crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), lignin (LIG), non-fibrous carbohydrates (NFC), starch, ether extract (EE), 48-h in vitro NDF digestibility (NDFD^{48h}), and total digestible nutrients (TDN). Fermentation end-products, including lactic acid (LA), acetic acid (AA), butyric acid (BA), and ammonia nitrogen (NH_3-N), were also quantified. The predictive robustness of the NIRS models was confirmed through cross-validation, which is an internal validation procedure where the calibration dataset is repeatedly split to evaluate the model's predictive performance. The models met the minimum acceptance criteria of a coefficient of determination (R^2) $\geq$ 0.90 and a residual predictive deviation (RPD) $\geq$ 3.0 for the cross-validated predictions. In a separate analysis, the pH of the silage was measured potentiometrically (mPA210 potentiometer, MS Tecnopon, Santa Rosa, Brazil) from an aqueous extract prepared with 25 g of silage and 225 mL of distilled water.

2.6. Statistical Analysis

Data were analyzed using Sisvar software version 5.8 (Build 92). When significant interactions were found ($p < 0.05$), the factors were analyzed separately. The data were subjected to the following model:

$$Yijk = \mu + Ci + Rj + C \times Rij + \varepsilon ijk \quad (2)$$

where $Yijk$ represents the dependent variable, μ the overall mean, Ci the effect of the cropping system, Rj the effect of row spacing, $C \times Rij$ the interaction effect, and εijk the random error. Means were compared by the Scott-Knott test at a 5% significance level ($p \leq 0.05$).

3. Results

3.1. Biomass Productivity of Sorghum-Grass Intercropping Systems

Significant differences ($p < 0.05$) were observed among cropping systems and row spacings for sorghum dry matter yield (SDMY) and total dry matter yield (TDMY) (Table 2).

Table 2. Forage yield and sorghum silage quality in different cropping systems and spatial arrangements.

Parameters	Cropping System			SEM	Row Spacing		SEM	*p*-Value		
	S	MS	ZS		45	90		C	R	C × R
SDMY, t/ha	22.95 a	21.34 a	16.96 b	0.76	22.46 a	18.38 b	0.62	<0.01	<0.01	0.11
TDMY, t/ha	22.95 a	22.91 a	20.14 b	0.74	23.17 a	20.83 b	0.61	0.02	0.01	0.67
GDMY, t/ha	-	1.57 b	3.17 a	0.20	0.71 b	2.44 a	0.16	<0.01	<0.01	<0.01
DMR, % ensiled DM	96.46	96.88	96.44	0.27	96.98 a	96.20 b	0.21	0.42	0.02	0.05
pH	4.03 b	4.13 a	3.97 b	0.03	4.05	4.03	0.03	<0.01	0.54	0.59
Lactic Acid, % DM	4.49	3.87	3.94	0.27	4.16	4.04	0.22	0.24	0.70	0.28
Acetic Acid, % DM	2.14	1.88	2.14	0.21	2.22	1.89	0.17	0.60	0.19	0.36
Butyric Acid, % DM	0.07 b	0.19 a	0.01 b	0.04	0.03	0.15	0.04	0.03	0.02	0.04
NH_3-N, % TN	0.54	0.52	0.53	0.06	0.51	0.54	0.05	0.97	0.70	0.85
Dry Matter, % FM	29.27 b	29.87 a	28.92 b	0.18	29.17	29.53	0.15	<0.01	0.10	<0.01
Ash, % DM	2.18	2.16	2.28	0.31	2.33	2.08	0.25	0.96	0.50	0.65
Crude Protein, % DM	7.23 a	6.79 b	6.80 b	0.10	6.73 b	7.15 a	0.08	0.01	<0.01	<0.01
NDF, % DM	75.54 a	75.04 a	73.46 b	0.51	75.52 a	73.84 b	0.42	0.03	0.01	0.19
ADF, % DM	50.38 b	51.23 a	49.61 b	0.41	50.43	50.38	0.34	0.04	0.90	0.12
Lignin, % DM	8.85	8.85	9.19	0.22	8.97	8.96	0.18	0.47	0.97	0.15
NFC, % DM	14.26 b	15.51 b	17.08 a	0.65	14.91	16.33	0.53	0.02	0.07	0.16
Starch, % DM	2.11	2.26	2.04	0.26	1.83 b	2.45 a	0.21	0.82	0.05	0.32
Ether Extract, % DM	2.98	2.81	2.68	0.10	2.67 b	2.98 a	0.08	0.15	0.02	0.26
$NDFD^{48h}$, % DM	44.25	44.25	42.13	0.97	43.08	44.00	0.80	0.23	0.43	0.41
TDN, % DM	53.75	53.88	53.50	0.42	53.08 b	54.33 a	0.35	0.82	0.02	0.06

SDMY: Sorghum dry matter yield; TDMY: Total dry matter yield (Sorghum + Grass); GDMY: Grass dry matter yield; DMR: Dry matter recovery; NH_3-N: Ammonia nitrogen; TN: Total nitrogen; FM: Fresh matter; NDF: Neutral detergent fiber; ADF: Acid detergent fiber; NFC: Non-fibrous carbohydrates; $NDFD^{48h}$: 48-h NDF digestibility; TDN: Total digestible nutrients; SEM: Standard error of the mean. Means within a row (for each factor) followed by the same lowercase letter do not differ significantly by the Scott-Knott test ($p > 0.05$). For significant interactions ($p \leq 0.05$), the decomposition of the means and their statistical separation are presented in the respective figures.

Among the cropping systems, the "ZS" intercrop resulted in the lowest SDMY ($p < 0.01$), at 16.96 t/ha, 23% lower than the average of the most productive treatments. The 'ZS' intercrop also recorded the lowest TDMY (20.14 t/ha), representing a 10% reduction compared to the sorghum monoculture (22.95 t/ha) and a 12% reduction compared to the 'MS' intercropping (22.91 t/ha). Regarding row spacing, the 45 cm spacing provided the highest SDMY and TDMY, with increases of 4.08 and 2.34 t/ha, respectively, compared to the 90 cm spacing.

An interaction ($p < 0.01$) was observed between cropping systems and row spacings for grass dry matter yield (GDMY) (Table 2 and Figure 2). This interaction revealed a clear pattern: the advantage of the wider row spacing (90 cm) was dramatically more pronounced for Zuri grass (ZS) than for Marandu grass (MS). Specifically, in the ZS system, the 90 cm spacing yielded approximately 3.17 t/ha of grass, which was about 37% higher than the average of the other treatment combinations.

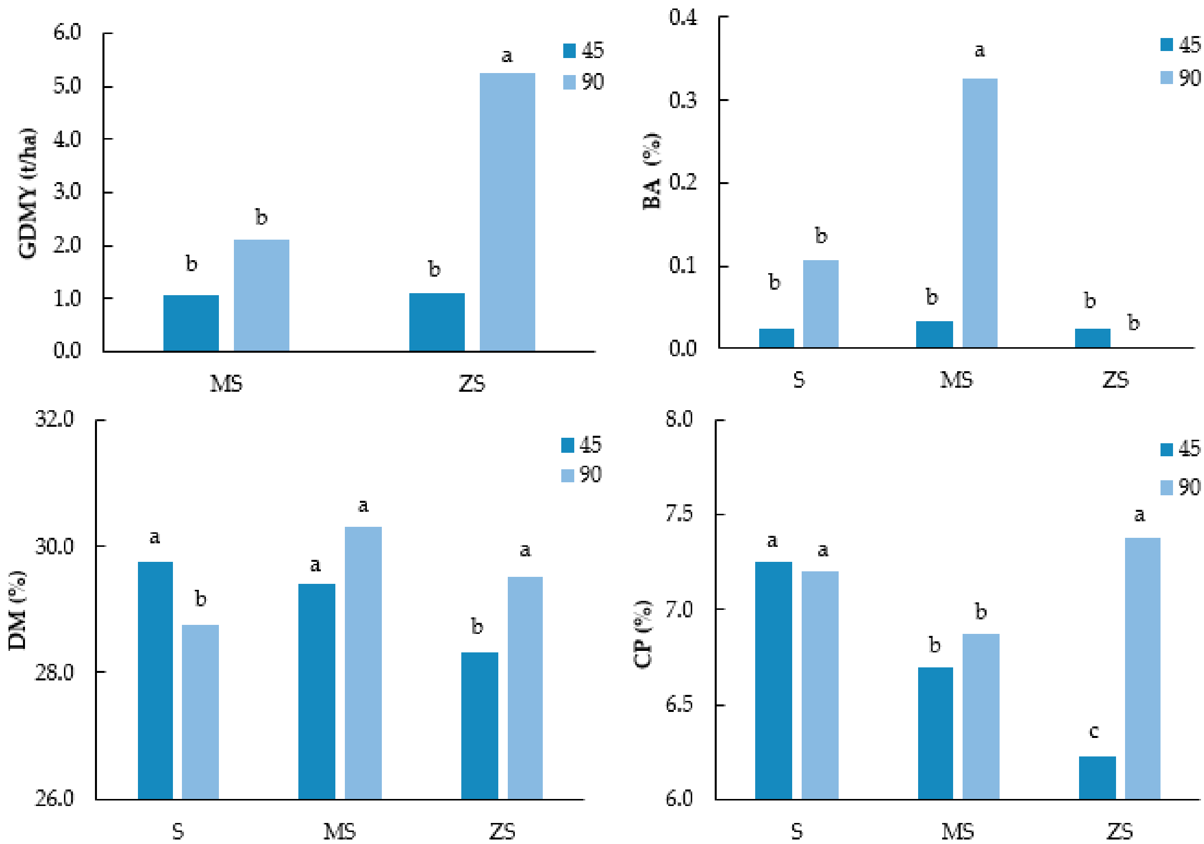

Figure 2. Grass dry matter yield (GDMY), butyric acid (BA), dry matter (DM), and crude protein (CP) content of silages as affected by different cropping systems and spatial arrangements in the municipality of Vicentina, Mato Grosso do Sul State, Brazil. S: Sorghum monoculture; MS: Marandu grass + Sorghum; ZS: Zuri grass + Sorghum. Distinct lowercase letters indicate significant differences by Scott-Knott test ($p \leq 0.05$).

3.2. Fermentative and Nutritional Quality of Sorghum Silages from Different Cropping Systems

Regarding dry matter recovery (DMR), no significant differences ($p > 0.05$) were observed among cropping systems, with values exceeding 96% of the ensiled DM in all treatments. For row spacings, the 45 cm spacing showed higher ($p < 0.05$) DMR values, with an increase of approximately 0.78% compared to the 90 cm spacing.

For pH values (Table 2), both the monocropped sorghum and the "ZS" intercrop showed the lowest values, with an average of 4.0, while the "MS" system recorded the highest pH, at 4.13.

Despite these variations, no significant differences ($p > 0.05$) were observed in lactic (LA) and acetic (AA) acid concentrations among treatments. The lowest concentrations of these acids were recorded in the "MS" system, with 3.87% LA and 1.88% AA. Similarly, there was no significant difference ($p > 0.05$) in NH_3-N concentrations among treatments (Table 2), with values remaining above 0.50% of total N; the highest value was observed in the monocropped sorghum silage (0.54%).

A significant interaction ($p < 0.05$) was observed between cropping systems and row spacings for butyric acid (BA) concentrations (Table 2 and Figure 2). The pattern revealed that the wider 90 cm spacing led to a substantial increase in BA concentration only in the Marandu grass intercropping (MS), whereas in the Zuri grass intercropping (ZS), BA remained low regardless of the row spacing. The highest value was recorded in the "MS" system with a 90 cm spacing, reaching 0.325% of DM. In the other treatments, no significant differences were observed, with an average BA concentration of 0.021% of DM.

A significant interaction ($p < 0.01$) was identified between cropping systems and row spacings for DM content (Table 2). The decomposition of this interaction revealed distinct responses to row spacing depending on the system. In the monocropped sorghum (S), DM% was significantly reduced at the wider 90 cm row spacing compared to the 45 cm spacing. In contrast, the MS system showed no significant response to row spacing. Conversely, in the ZS system, DM% was significantly higher at the 90 cm spacing compared to the 45 cm spacing. Overall, all produced silages had average DM contents above 29% (Figure 2).

A significant interaction was observed between cropping systems and row spacings for crude protein (CP) content (Table 2; Figure 2). The key finding was that the wider 90 cm spacing resulted in a significantly higher CP content only in the Zuri grass intercropping (ZS). In this specific system "ZS" at 90 cm, the CP content was equivalent to that of the monoculture (7.27% of DM). Conversely, in the same "ZS" intercropping but at the 45 cm spacing, the lowest CP value of the entire study was recorded (6.22% of DM). In the other treatments (S and MS), row spacing did not drastically alter the silage protein content.

Significant differences ($p < 0.05$) were observed among cropping systems for neutral detergent fiber (NDF) and acid detergent fiber (ADF) contents (Table 2). The lowest values were recorded in the "ZS" system, with 73.46% NDF and 49.61% ADF, representing reductions of approximately 1.83% and 2.35%, respectively, compared to the average of the other treatments.

Regarding spacing, a significant difference ($p < 0.05$) was observed only for NDF content, with the highest value recorded at the 45 cm spacing (75.52% NDF in DM). On the other hand, no significant differences ($p > 0.05$) were identified for lignin contents, which showed an average value of 8.96% of DM, regardless of the cropping systems or spacings evaluated.

In contrast to the fibrous fractions (NDF and ADF), non-fibrous carbohydrates (NFC) contents were higher in the "ZS" system, with a value of 17.08% of DM, approximately 12% above the average observed in the monocropped and "MS" systems (Table 2). No significant differences ($p > 0.05$) were found for starch content and $NDFD^{48h}$. The average starch content was 2.13% of DM across cropping systems and spacings, while $NDFD^{48h}$ showed an average value of 43.54% of DM, regardless of treatment.

Conversely, significant differences ($p < 0.05$) were observed between the tested spacings for ether extract (EE) and total digestible nutrients (TDN) contents, with the highest values recorded at the 90 cm spacing, reaching 2.98% and 54.33% of DM, respectively. Overall, the cropping systems had an average EE content of 2.82% of DM, and all silages had TDN contents above 53%.

4. Discussion

4.1. Biomass Productivity of Sorghum-Grass Intercropping Systems

Numerous studies have reported reductions in sorghum productivity in intercropping systems, with these reductions being highly dependent on the grass species used and environmental conditions [27–29]. According to [30,31], competition for light, nutrients, and water is cited as the main factor responsible for these losses, potentially causing 15 to 97% reductions in sorghum growth and yield. In the present study, *Urochloa brizantha* was less competitive against biomass sorghum, resulting in statistically equivalent dry matter yields compared to the monoculture.

Conversely, the intercrop with Zuri grass showed significant reductions in both sorghum dry matter yield (SDMY) and total system yield (TDMY) (Table 2). Zuri (*Megathyrsus maximus*) is characterized by vigorous growth and dense leaf architecture, which can reduce light interception by the sorghum, limiting its development [15]. Similar results were observed by [27], who reported lower sorghum grain yield when intercropped with *M. maximus*, while intercropping with *U. brizantha* favored plant productivity, corroborating the findings of the present work.

Despite the approximately 26% reduction in sorghum biomass yield in the intercrop with Zuri grass (Table 2), it is important to highlight that this grass showed the highest forage accumulation when sown at the 90 cm spacing. This result can be particularly advantageous in Crop-Livestock Integration (CLI) systems when the main goal is the efficient establishment or recovery of pasture after the harvest of the annual crop.

Cultivars of the genus *M. maximus*, such as BRS Zuri, have stood out in livestock production due to their high dry matter yield [32] and superior nutritional quality, providing higher animal weight gains compared to species of the genus *Urochloa*. In a study by [33], the authors observed a productive superiority of grasses of the genus *Megathyrsus* compared to those of the genus *Urochloa*.

Thus, the reduction in sorghum yield observed in this intercrop may be offset by the availability of higher nutritive value forage in the period following harvest, as evidenced in this study, contributing to improved animal performance.

Beyond zootechnical benefits, intercropping with grasses plays a fundamental role in the sustainability of agricultural systems, contributing to increased biomass for no-till farming, weed control, nutrient cycling, improvement of soil health, production diversification, and reduction of greenhouse gas emissions [34]. Specifically, *M. maximus* has greater potential than *U. brizantha* to increase soil carbon and nitrogen stocks, in addition to favoring water conservation and soil structural stability [29], which can also be an advantage in the long term.

Initially, it was expected that increasing the row spacing would allow more light into the system and consequently higher productivity of both sorghum and the intercropped grasses. However, this strategy favored greater growth vigor of the grasses, which may have resulted in the 18% reduction in SDMY and 10% reduction in TDMY compared to the narrower spacing (Table 2). Furthermore, the climatic conditions during the experiment, especially the well-distributed rainfall, may have favored denser sorghum growth even under competition.

These results highlight the complexity of managing intercropping systems, where interactions between species are strongly influenced by soil-related factors, water regime, and other local climatic characteristics. In this context, this type of research is fundamental to support the choice of complementary forage species and to define spatial arrangements that favor the growth and performance of both crops [4,35].

4.2. Fermentative and Nutritional Quality of Sorghum Silages from Different Cropping Systems

DMR in silage represents the proportion of the originally stored dry matter that is effectively preserved at the end of the fermentative process, an essential parameter for evaluating the efficiency of the ensiling process [36]. This indicator is affected by losses from effluent production, gas release, and aerobic deterioration of the top layer of silos [37], with high DMR values reflecting lower nutrient loss and better silage quality [25]. In the present study, DMR values were above 96% (Table 2), considered high compared to data usually reported for biomass sorghum hybrid silages [38]. High DMR values can be attributed to the effective combination of an adequate packing density (~820 kg FM/m^3), which minimized air trapped in the silo, and the prevalence of desirable fermentation conditions. These results indicate that the ensiling conditions were adequate, favoring the predominance of desirable fermentations and minimizing losses during the process.

Silage pH is an important indicator of its acidity and fermentative quality. During the ensiling process, lactic acid, produced by lactic acid bacteria with a pKa of 3.86, is primarily responsible for the pH drop, being 10 to 12 times stronger than other common organic acids like acetic acid (pKa 4.75) and propionic acid (pKa 4.87) [25]. In silages with low dry matter (<30%), the concentration of lactic acid can be even higher, favoring the pH drop [37]. In the present study, the "MS" system showed slightly higher pH values than the other treatments (Table 2).

Nonetheless, the average pH value of the silages was 4.04, which falls within the range considered adequate for silages of tropical grasses, like sorghum and corn, according to criteria established by [25]. The contents of lactic and acetic acids did not differ among treatments and remained compatible with the technical parameters recommended in the literature, indicating the occurrence of a predominantly homolactic fermentation.

The concentration of butyric acid, in turn, remained low in all treatments, including the "MS" intercrop at the wider spacing, which evidences a well-conducted fermentation with limited activity of undesirable microorganisms, particularly those belonging to the genus *Clostridium*.

Corroborating these results, the ammonia nitrogen (NH_3-N) levels remained low, indicating less protein degradation during the fermentative process and reinforcing the hypothesis that clostridial activity was effectively controlled. It is important to note that higher NH_3-N values are commonly associated with legume silages or materials with high moisture content, as reported by [39], which was not observed under the conditions of this experiment.

Regarding DM content, even though the monocrop and "ZS" systems showed the lowest percentage at the 90 cm and 45 cm spacings, respectively (Table 2; Figure 2), the sorghum silages averaged 29% DM, a value that allows for adequate fermentation [25]. Biomass sorghum has high moisture content at harvest, making it difficult to achieve silages with DM contents above 30% [40]. This behavior is associated with the high proportion of stalks and water accumulation in the tissues, even at advanced developmental stages [38]. Consequently, ensiling this material requires special attention to the cutting point and, in some cases, the use of additives or absorbent materials to avoid excessive effluent production.

Intense interspecific competition for nitrogen with Zuri grass may have limited the availability of this nutrient for biomass sorghum, restricting its protein synthesis capacity [17]. Simultaneously, the competition for resources like light, water, and nutrients may have compromised the development of structural tissues, resulting in lower deposition of stalk and panicle, which would explain the lower NDF and ADF contents observed in the "ZS" intercrop [41].

The reduction in fibrous mass may also have caused less dilution of soluble carbohydrates, favoring the relative accumulation of NFC in the "ZS" intercrop (Table 2), as reported by [42] for materials with less structured cell walls. These results indicate that competition in the "ZS" intercrop altered the carbon and nitrogen allocation in sorghum plants, reducing the synthesis of cell wall components and favoring the accumulation of soluble sugars [43].

A higher NFC concentration is desirable from a fermentative standpoint, as these compounds are highly degradable, promoting a rapid pH drop and contributing to silage preservation [25,44]. However, as reported earlier, this higher proportion of residual NFC did not result in a better fermentative profile of the silages evaluated in the present study.

The lower sorghum productivity observed in the cropping systems with wider row spacing (90 cm) possibly resulted in plants with reduced height and stalk diameter. This morphological limitation tends to reduce the deposition of structural cell wall components, like cellulose and lignin, reflecting in lower accumulation of fibrous fractions such as NDF and ADF [45].

Consequently, the lower proportion of structural material favors the accumulation of more easily digestible compounds, increasing the contents of total digestible nutrients (TDN) [46,47]. These factors help explain the higher TDN values observed in the present study (Table 2), showing that more restricted vegetative development may favor the nutritional quality of the produced forage.

Furthermore, the higher Total Digestible Nutrient (TDN) content observed at the 90 cm row spacing can be explained by a shift in internal carbon partitioning within the plant [48]. The less dense vegetative growth in this wider spatial arrangement, evidenced by the lower biomass yield (Table 2), likely limited the plant's investment in structural cell wall components.

This hypothesis is supported by the concomitant trend of lower fiber (NDF) content at this spacing. Consequently, a greater proportion of photoassimilates may have been allocated to the synthesis of non-fibrous [17,48], highly digestible compounds, reflected in the numerical increase in NFC and, ultimately, the higher TDN value.

This redistribution of carbon, rather than a difference in physiological stage at harvest, appears to be the underlying mechanism for the improved silage nutritional quality at the wider row spacing.

5. Conclusions

Simultaneous sowing of biomass sorghum with Marandu palisade grass did not adversely affect sorghum silage biomass yield, fermentative profile, or nutritional quality compared to monoculture. In contrast, intercropping with Zuri grass significantly enhanced subsequent pasture establishment but at the cost of reduced sorghum yield.

Among the spatial arrangements, the 45 cm row spacing was the most efficient for maximizing total forage biomass production, whereas the 90 cm spacing favored grass growth and improved specific sorghum silage quality parameters. These results provide clear practical applications: the sorghum-Marandu intercropping at 45 cm is ideal for silage production, while the sorghum-Zuri intercropping at 90 cm optimizes pasture recovery.

Future research should validate these findings across multiple growing seasons and diverse Brazilian agroecological zones, including other cultivars of tropical grasses, to develop robust, region-specific recommendations.

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Abbreviations

The following abbreviations are used in this manuscript:

AA	Acetic Acid
ADF	Acid Detergent Fiber
BA	Butyric Acid
C	Cropping System
CLI	Crop-Livestock Integration
CP	Crude Protein
DAP	Days after planting
DM	Dry Matter
DMR	Dry Matter Recovery
EE	Ether Extract
FM	Fresh Matter
GDMY	Grass Dry Matter Yield
LA	Lactic Acid
MS	Sorghum + Marandu grass
NDF	Neutral Detergent Fiber
$NDFD^{48h}$	48-h NDF Digestibility
NFC	Non-Fibrous Carbohydrates
NH_3-N	Ammonia Nitrogen
NIRS	Near-Infrared Spectroscopy
R	Row Spacing
S	Sorghum Monoculture
SDMY	Sorghum Dry Matter Yield
SEM	Standard Error of the Mean
TDMY	Total Dry Matter Yield
TDN	Total Digestible Nutrients
TN	Total Nitrogen
ZS	Sorghum + Zuri grass

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