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Productivity and Fermentative and Nutritional Quality of Silages from Biomass Sorghum Intercropped with Tropical Grasses

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Abstract

Crop–livestock integration is widely adopted as a strategy for recovering degraded pastures. In this system, intercropping crops such as sorghum with tropical grasses enables the harvest of sorghum for silage while simultaneously establishing a new pasture. However, interspecific competition for resources can limit sorghum development and yield, potentially compromise the fermentation process and reduce the nutritional quality of the silage. Therefore, this study aimed to evaluate the agronomic performance, fermentative characteristics, and chemical–bromatological composition of silages produced from different biomass sorghum-grass intercropping systems. The experiment was conducted in a randomized block design with a 3 $\times$ 2 factorial arrangement: three cropping systems [sorghum monoculture, sorghum intercropped with Marandu grass (S + M), and sorghum intercropped with Zuri grass (S + Z)] and two sorghum row spacings (45 and 90 cm). The S + Z intercropping system with 90 cm row spacing showed the highest total dry matter yield (16.42 t/ha). It also presented better fermentative parameters, such as pH (4.02) and lactic acid (5.31%DM) and superior nutritional quality, with lower fiber content and higher concentrations of NFC (24.79%DM), TDN (59.75%DM), and digestibility. It is concluded that intercropping biomass sorghum with Zuri grass at 90 cm spacing is the most promising strategy for producing high-quality silage.

Keywords: degraded pasture; ensiling process; forage production; intercropping; lactic acid

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1. Introduction

Brazil has 109.7 million hectares of cultivated pastures with some level of degradation, representing approximately 60% of the total pastureland, which is estimated at 177 million hectares [1]. This condition reduces livestock system productivity, as degraded pastures face higher susceptibility to weeds, pests, and diseases while yielding less biomass [2]. Thus, pasture renovation emerges as a strategic alternative to enhance the productive efficiency of grazing areas, reducing the need to clear new agricultural frontiers [3].

Crop–Livestock Integration (CLI) has proven to be an effective strategy for recovering degraded pastures, offering economic, productive, and environmental benefits superior to monoculture systems [4]. Key advantages of CLI systems include improvements in soil physical, chemical, and biological properties, reduced weed infestation and pesticide use, diversification of agricultural production, increased profitability, and sustainable intensification of livestock activities.

Another relevant aspect of CLI is the potential to offset the costs of establishing new pastures through the harvest of intercropped annual crops [5]. Crops such as corn and sorghum, when used as the crop component, provide financial returns within the first agricultural cycle—either through grain sales or high-quality silage production. This partial or full return on investment before the perennial pasture is fully established represents a significant advantage over conventional pasture renovation, where returns are slower and often depend solely on animal performance. Thus, CLI becomes economically more attractive by combining pasture recovery with short-term revenue generation.

In the Brazilian savannas (Cerrado region), CLI has been implemented through the intercropping of annual crops (e.g., corn, soybeans, sorghum) with perennial forage grasses of the genera *Megathyrsus* and *Urochloa*. Among these, sorghum stands out for its broad adaptability, high dry matter productivity, good nutritional quality, and regrowth capacity—especially under low-fertility and water-stress conditions [6,7].

In intercropping systems involving grain sorghum and forage grasses, it is common practice to delay the sowing of the forage species by 7 to 14 days after planting the cash culture (e.g., sorghum, corn) [8–10]. This approach aims to reduce competition for light, water, and nutrients during the early stages of crop development. However, it requires an additional field operation, leading to increased labor and machinery costs.

In contrast, biomass sorghum hybrids exhibit more vigorous growth, taller stature, and greater competitive ability [11]. These traits may allow for simultaneous sowing with forage grasses without significantly affecting sorghum productivity, while also simplifying field operations. This strategy not only lowers operational costs but also promotes rapid pasture establishment following harvest, thereby enhancing the efficiency and sustainability of integrated production systems. Nevertheless, the success of this approach depends on the appropriate choice of forage species, row spacing, and management practices suited to local soil and climatic conditions.

Given the limited research on intercropping biomass sorghum with forage grasses under Cerrado conditions, this study was conducted based on the following hypotheses: (i) simultaneous sowing of a biomass sorghum hybrid with Marandu (*Urochloa brizantha*) and Zuri (*Megathyrsus maximum*) grasses does not compromise biomass yield or the fermentative and nutritional quality of the resulting silage; and (ii) a 45 cm row spacing promotes greater biomass accumulation and enhances silage quality. Therefore, the objective of this study was to identify the most efficient intercropping combination and spatial arrangement between biomass sorghum and the Marandu and Zuri grasses, aiming to maximize forage yield and the fermentative and nutritional quality of the produced silage.

2. Materials and Methods

2.1. Experimental Area Characterization

The experiment was conducted at the experimental field of Embrapa Agropecuária Oeste (22°16′44″ S, 54°49′10″ W; altitude 401 m) in Dourados, Mato Grosso do Sul, Brazil. The regional climate is classified as Cwa (humid subtropical with rainy summers) under the Köppen system [12]. The soil is classified as dystroferric Red Yellow Latosol—LVAd soil type according to the Brazilian Soil Classification System—SiBCS [13]. Figure 1 illustrates the rainfall balance and historical average record. Figure S1 shows the temperature and the photosynthetically active radiation during the experimental period.

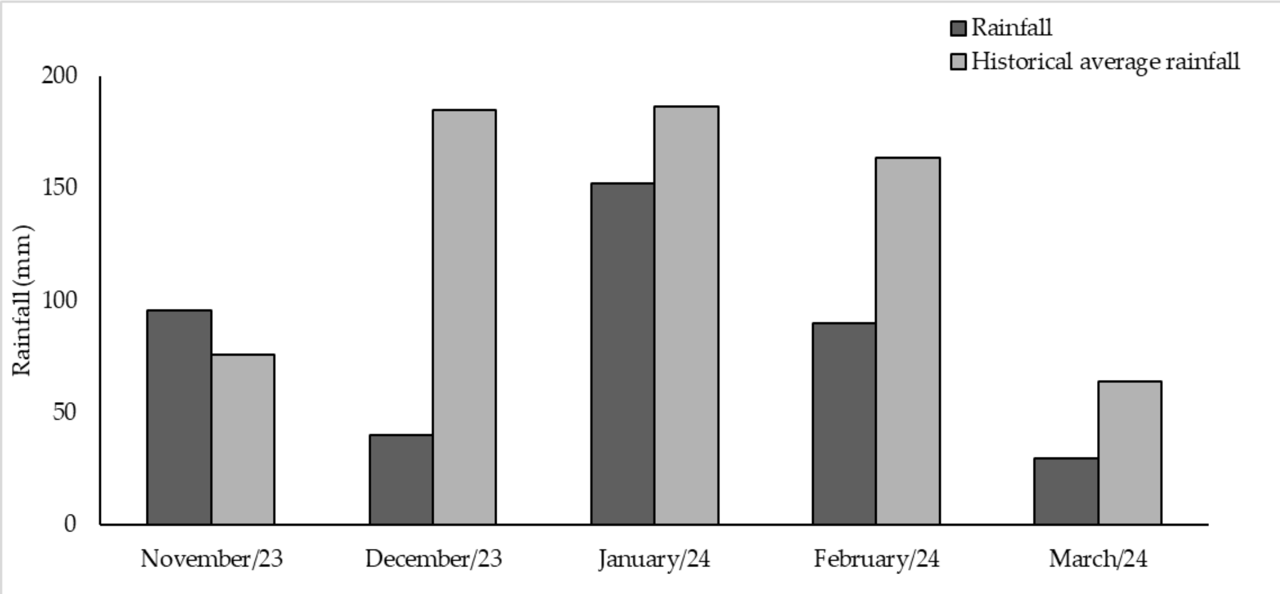

Figure 1. Historical average rainfall (2005–2024) compared to rainfall recorded during the experimental period. Source: Guia Clima—Embrapa.

2.2. Soil Sampling and Fertilization

In September 2023, soil samples were collected from the 0–20 cm layer for physical and chemical analysis. The soil characteristics are displayed in Table 1.

Table 1. Chemical and physical attributes of the soil in the experimental area (0–20 cm depth).

Parameter	Value	Unit
Soil pH ($CaCl_2$)	4.9	-
Phosphorus	9.3	mg/L
Potassium	6.4	mmolc/L
Calcium	31	mmolc/L
Magnesium	13.6	mmolc/L
Aluminum	0.7	mmolc/L
Potential Acidity (H + Al)	41.5	mmolc/L
Sum of Bases	51	mmolc/L
Cation Exchange Capacity	92.5	mmolc/L
Base Saturation	55.1	%
Aluminum Saturation	1.4	%
Copper	0.2	mmol/L
Iron	0.87	mmol/L
Manganese	1.75	mmol/L
Zinc	0.04	mmol/L
Clay	637	g/kg
Sand	205	g/kg
Silt	158	g/kg
Organic Matter	27.89	g/kg

All physical and chemical soil analyses were carried out according to the methodology described by [14]. At sowing, a basal fertilization of 300 kg/ha of 08–20–20 (N-P-K) was applied. Subsequently, topdressing was applied on December 26, 2023, with 150 kg/ha of N in the form of ammonium sulfate, which was surface-applied.

2.3. Experimental Design

A randomized complete block design was adopted in a 3 × 2 factorial arrangement. Treatments consisted of three cropping systems [biomass sorghum monoculture, sorghum intercropped with *Urochloa brizantha* cv. Marandu (S + M), and sorghum inter-cropped with *Megathyrsus maximus* cv. Zuri (S + Z)] combined with two sorghum row spacings (45 cm and 90 cm), totaling six treatments (Figure 2). The biomass sorghum hybrid Agri 002E (Latina Seeds) was used. Sowing was performed on 17 November 2023, using a Semeato SHM 15/17 planter equipped with small-seed boxes.

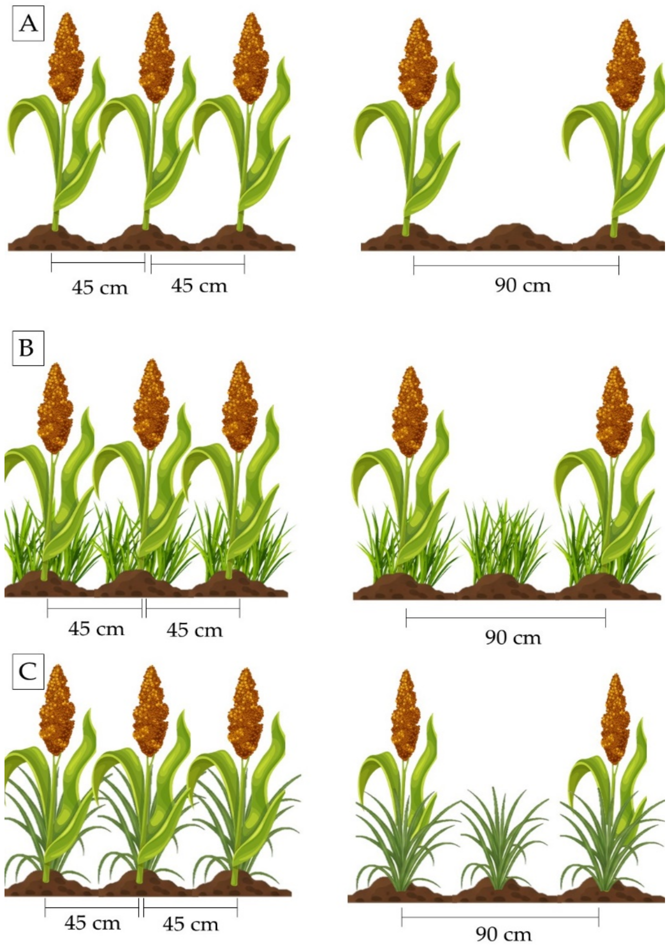

Figure 2. Experimental treatments: (**A**) Biomass sorghum monoculture; (**B**) Intercropping of sorghum with Marandu palisadegrass; (**C**) Intercropping of sorghum with Zuri palisadegrass, with two sorghum row spacings.

The target plant population was 120,000 sorghum plants per hectare. Each experimental plot measured 12 m in length and comprised seven rows at 45 cm spacing or four rows at 90 cm spacing, with four replicates per treatment. Dry matter production of sorghum and grasses was evaluated by harvesting two central rows per plot. Plants were cut at approximately 127 days after planting, maintaining a 10 cm stubble height to simulate silage harvest.

2.4. Sample Collection and Chemical–Bromatological Analysis

Fresh forage weight was recorded, and subsamples (~300 g per crop and plot) were oven-dried at 60 °C until constant weight to determine dry matter (DM) content. Total dry matter yield (TDMY), sorghum dry matter yield (SDMY), and grass dry matter yield (GDMY) in each intercrop system were calculated. For silage production, only sorghum plants from central rows were processed in a stationary forage chopper to achieve a 1.5 cm particle size. The chopped material was homogenized and packed into experimental silos made of PVC tubes (10 cm diameter × 50 cm height; 3.8 L usable volume) at an average density of 820 kg/m^3. Each silo contained 300 g of sand at the base for effluent drainage, separated from the forage by a fine mesh. Silos were sealed with double-faced plastic film (black/white) and adhesive tape, then stored in a climate-controlled environment at a constant temperature of 25 °C.

All silo components and ensiled forage were weighed before and after 60 days of storage to calculate DM recovery, using the following formula proposed by [15]:

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

where 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).

Upon opening, silage samples were homogenized for chemical analysis. A portion was scanned using a Foss 5000 Transport NIRS system (Eden Prairie, MN, USA) with WinISI 4.6.11 software (FOSS Analytical A/S, Denmark) and Dairy One Forage Laboratory (Ithaca, NY) calibrations to determine DM, ash, crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), lignin (LIG), non-fibrous carbohydrates (NFC), starch, ether extract (EE), 48h NDF digestibility (NDFD48), and total digestible nutrients (TDN). Lactic acid (LA), acetic acid (AA), butyric acid (BA), and ammonia nitrogen (NH_3-N) concentrations were also analyzed. Model performance was verified through cross-validation and, when applicable, external validation, considering the coefficient of determination (R^2), standard error of validation (SEV), and residual predictive deviation (RPD), with minimum acceptance criteria of $R^2 \geq 0.90$ and RPD ≥ 3.0. Frozen samples were thawed, and pH was measured in aqueous extract (25 g forage + 225 mL distilled water) using a digital potentiometer (mPA210, MS Tecnopon).

2.5. Statistical Analysis

Data were analyzed with Sisvar 5.8 (Build 92). When interaction effects were significant ($\alpha \leq 0.05$), factors were analyzed separately; otherwise, main effects were evaluated. Means were compared using Scott-Knott's test ($p \leq 0.05$). The silage data followed the model:

$$\mathrm{Yijk} = \mu + \mathrm{Si} + \mathrm{SAj} + \mathrm{S} \times \mathrm{SAij} + \varepsilon\mathrm{ijk}$$

where Yijk = dependent variable, μ = overall mean, Si = cropping system effect (fixed; i = biomass sorghum monoculture, S + M, S + Z), SAj = row spacing effect (fixed; j = 45 cm, 90 cm), S × SAij = interaction effect, and εijk = random error.

3. Results

3.1. Productivity of Biomass Sorghum and Grass Intercropping Systems

The experimental results and their statistical interactions are detailed in Table 2 and illustrated in Figure 3.

A significant interaction ($p < 0.01$) was observed between cropping systems and row spacings for both sorghum dry matter yield (SDMY) and total dry matter yield (TDMY) (Table 2; Figure 3). At 45 cm spacing, the S + Z intercrop achieved the highest SDMY (12.75 t/ha), statistically similar to the monoculture (11.34 t/ha) but significantly higher than the S + M system (9.15 t/ha). This indicates that under narrow spacing, Zuri grass was less competitive than Marandu grass.

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

Parameters	Cropping System (C)			SEM	Row Spacing (R)		SEM	*p*-Value		
	Monocrop	S + M	S + Z		45	90		C	R	C*R
SDMY, t/ha	9.90	9.77	12.03	0.331	10.95	10.19	0.270	<0.01	0.07	<0.01
TDMY, t/ha	9.90	10.78	15.19	0.337	11.54	12.37	0.476	<0.01	0.05	<0.01
GDMY, t/ha	-	1.00	3.15	0.168	0.59	2.17	0.137	<0.01	<0.01	<0.01
DMR, % ensiled DM	93.85	94.88	95.29	0.559	94.93	94.42	0.457	0.20	0.44	0.61
pH	4.00	4.02	4.04	0.009	4.02	4.02	0.012	<0.01	0.87	<0.01
LA, % DM	5.95	4.71	5.23	0.113	5.48	5.11	0.092	<0.01	0.01	<0.01
AA, % DM	0.84	0.60	0.78	0.103	0.91	0.56	0.089	0.27	<0.01	0.42
BA, % DM	ND *	ND	ND	ND	ND	ND	ND	-	-	-
NH3-N, % TN	0.42 a	0.30 b	0.38 a	0.020	0.36	0.36	0.167	<0.01	0.65	0.21
DM, % FM	27.42 b	28.97 a	29.41 a	0.310	28.45	28.75	0.253	<0.01	0.41	0.16
Ash, % DM	3.94	2.96	2.55	0.177	3.30	2.99	0.145	<0.01	0.14	<0.01
CP, % DM	9.10 a	8.68 b	8.66 b	0.127	8.78	8.84	0.104	0.04	0.70	0.16
NDF, % DM	63.61	62.33	62.64	0.440	63.01	62.71	0.359	0.13	0.56	0.28
ADF, % DM	41.46 a	39.44 b	40.16 b	0.378	40.72	39.99	0.308	<0.01	0.11	0.32
Lignin, % DM	7.55 a	6.99 b	7.45 a	0.131	7.33	7.33	0.107	0.02	0.96	0.47
NFC, % DM	21.85 b	25.03 a	24.79 a	0.480	23.37	24.41	0.392	<0.01	0.08	0.22
Starch, % DM	2.48	3.29	2.89	0.291	3.13	2.63	0.238	0.17	0.15	0.02
EE, % DM	3.41 a	3.10 b	3.21 b	0.058	3.317	3.17	0.047	<0.01	0.04	0.06
NDFD48h, % DM	51.75	53.75	51.75	0.712	52.00	52.83	0.581	0.10	0.32	<0.01
TDN, % DM	58.13 b	60.13 a	59.75 a	0.289	59.17	59.50	0.236	<0.01	0.33	0.17

C: Cropping system; R: Row spacing; S + M: Sorghum + Marandu grass; S + Z: Sorghum + Zuri grass; SDMY: Sorghum dry matter yield; TDMY: Total dry matter yield (Sorghum + Grass); GDMY: Grass dry matter yield; DMR: Dry matter recovery; LA: Lactic acid; AA: Acetic acid; BA: Butyric acid; NH_3-N: Ammonia nitrogen; TN: Total nitrogen; FM: Fresh matter; DM: Dry matter; CP: Crude protein; NDF: Neutral detergent fiber; ADF: Acid detergent fiber; NFC: Non-fibrous carbohydrates; EE: Ether extract; NDFD48h: 48 h NDF digestibility; TDN: Total digestible nutrients; SEM: Standard error of the mean. Distinct lowercase letters within the same row indicate significant differences by Scott-Knott test ($p \leq 0.05$). * ND: Not detected.

At 90 cm spacing, the S + Z system again produced the highest SDMY (11.30 t/ha), while both the monoculture (8.46 t/ha) and S + M (8.46 t/ha) systems yielded significantly less. This suggests that wider rows negatively affected sorghum growth unless intercropped with the less competitive Zuri grass.

A similar pattern was found for TDMY, which includes the combined yield of sorghum and grass. The lowest TDMY was recorded in sorghum monoculture at 90 cm and in the S + M intercrop at 45 cm (mean: 8.58 t/ha). In contrast, the S + Z intercrop at 90 cm spacing reached the highest TDMY (16.42 t/ha), representing a 101% increase compared with the least productive systems, mainly due to the substantial contribution of Zuri grass (GDMY) at this spacing.

The analysis also confirmed a significant interaction ($p < 0.01$) for grass dry matter yield (GDMY). The S + Z system consistently outperformed the others across all spacings (Figure 3), with its yield at 90 cm (4.12 t/ha) being approximately 69% and 215% higher than the S + Z at 45 cm and the S + M systems at any spacing, respectively.

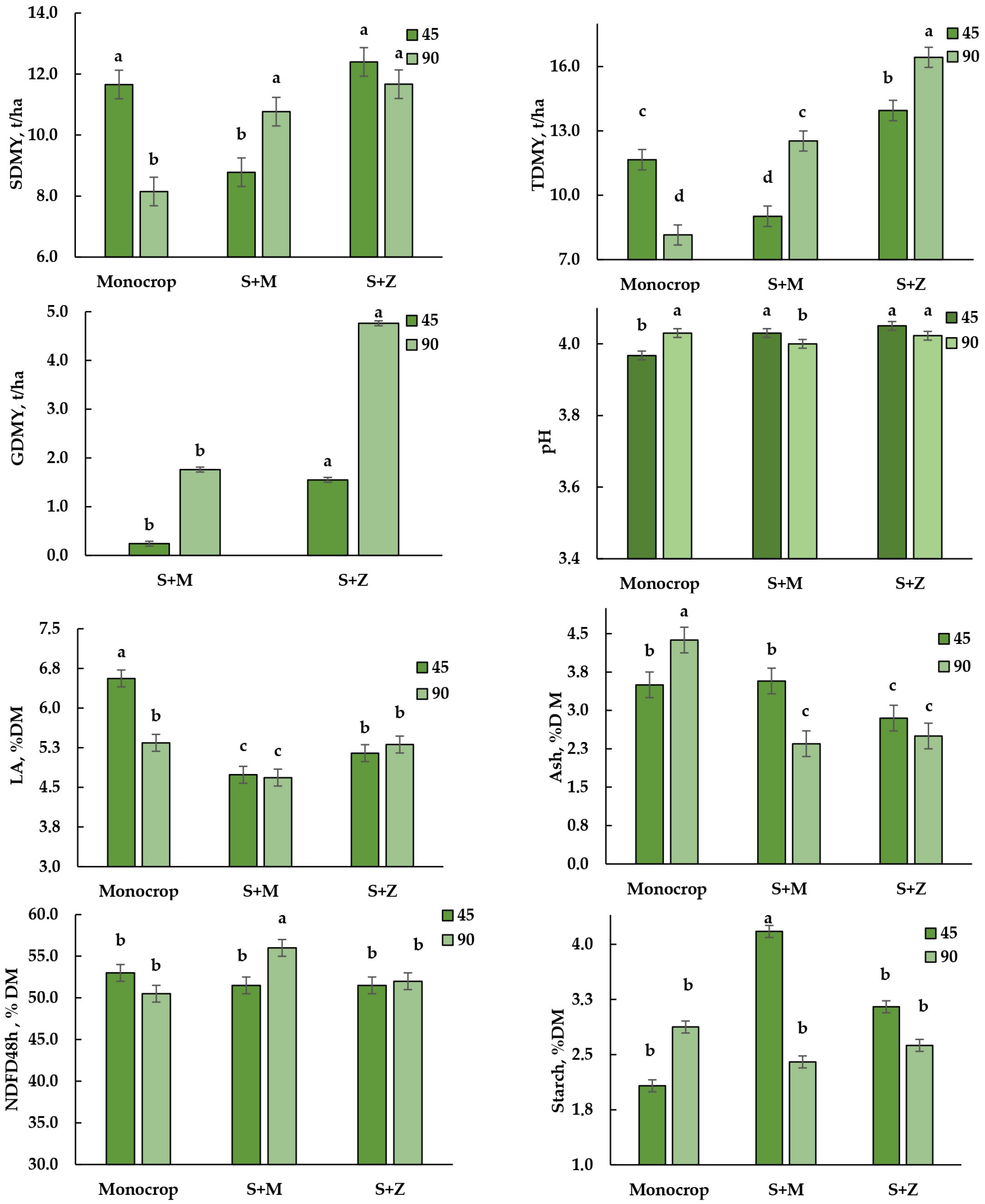

Figure 3. Sorghum dry matter yield (SDMY), total dry matter yield (TDMY), and grass dry matter yield (GDMY), pH, lactic acid (LA), ash content, starch, and 48 h NDF digestibility (NDFD48h) in different cropping systems and spatial arrangements. S + M = Sorghum + Marandu grass; S + Z = Sorghum + Zuri grass. Distinct lowercase letters indicate significant differences by Scott-Knott test ($p \leq 0.05$).

3.2. Fermentative and Nutritional Parameters of Biomass Sorghum Silages

Dry matter recovery (DMR) after ensiling showed no significant differences among treatments ($p > 0.05$), with all values exceeding 93%, indicating excellent preservation across all silages. The maximum DMR (95.29%) was recorded in S + Z silages. These consistently high DMR values confirm that ensiling was efficient under all management strategies, with minimal dry matter losses.

Significant interactions were detected for key fermentation parameters. The lowest pH values (mean: 3.98) occurred in biomass sorghum monoculture at 45 cm spacing and in S + M at 90 cm spacing (Figure 3). Lactic acid (LA) concentrations were significantly lower in S + M systems (mean: 4.71% of DM), while the monoculture at 45 cm spacing showed the highest LA accumulation (6.5% of DM). The S + Z systems presented intermediate LA levels (5.22% of DM). Acetic acid (AA) concentrations were affected only by spacing, with higher values at 45 cm (0.91% DM) compared to 90 cm (0.56% DM). Overall, fermentation was more homolactic (higher LA:AA ratio) at 90 cm spacing and in the S + Z system.

Butyric acid (BA) was undetectable in all samples, indicating absence of clostridial spoilage. Ammonia nitrogen (NH_3-N) as a percentage of total nitrogen differed among systems ($p < 0.01$), with S + M showing the lowest values (0.30%), suggesting reduced proteolysis.

Regarding chemical composition, monoculture sorghum silages had significantly lower dry matter (mean: 27.42% of fresh matter; $p < 0.01$) compared to intercrops. They also showed higher ash content, with the highest value (4.37% of DM) recorded at 90 cm spacing, whereas S + Z silages had the lowest ash levels. Monoculture silages further presented higher crude protein (CP), acid detergent fiber (ADF), lignin (LIG), and ether extract (EE) contents ($p < 0.05$), indicating a chemical profile with more cell contents (protein, EE) and less digestible fiber fractions.

In contrast, intercrops (S + M and S + Z) were superior in non-fibrous carbohydrates (NFC) and total digestible nutrients (TDN). Significant interactions ($p < 0.05$ and $p < 0.01$) were found for starch concentration and 48 h NDF digestibility (NDFD48h). Starch peaked in S + M at 45 cm spacing (4.17%), while the highest NDFD48h (56%) was observed in S + M at 90 cm spacing (Figure 3). The greater NFC and TDN in intercrop silages translate directly into higher potential energy availability for ruminants.

4. Discussion

4.1. Productivity of Biomass Sorghum and Grass Intercropping Systems

The biomass yields observed in this study, which were below 12.5 t/ha (Table 2), are considerably lower than the average yields typically reported for biomass sorghum hybrids in Brazil [16]. In a study by [17], four sorghum cultivars (SHS 400, 1G220, BRS 310, and 0992045) grown in semi-arid regions produced grain yields ranging from 1.7 to 5.1 t/ha. This wide variation was attributed to water availability, with higher yields recorded where cumulative rainfall reached up to 519 mm. These findings emphasize that although sorghum is recognized for its drought tolerance, precipitation strongly determines its productivity: water deficit does not kill the crop, but it significantly reduces yield potential.

Sorghum generally requires 450–550 mm of water throughout its growth cycle, with optimal yields occurring when cumulative rainfall exceeds 500 mm [18,19]. In this study, precipitation totaled only about 400 mm, with a marked deficit in the final stages of growth (Figure 1), which likely contributed to the reduced yields observed. Water shortages at these stages are known to impair photosynthesis and nutrient uptake, ultimately decreasing productivity [20].

Extensive research demonstrates that cereal–grass intercropping systems enhance biomass production through complementary growth cycles, plant architecture, and root depth stratification [21,22]. In the present study, the poor performance of sorghum monoculture at 90 cm spacing illustrates the vulnerability of wide-row systems under rainfed conditions (Figure 1). Reduced plant population density and the absence of inter-row cover likely intensified soil water evaporation, compromising soil water retention and plant development. This highlights a key risk of wide-row monocultures in water-limited environments.

In contrast, the better performance observed in the intercropping systems—especially S + Z at 90 cm—highlights the potential of strategic intercropping to alleviate drought stress. The forage grasses likely functioned as living mulches, helping to lower soil temperature and reduce evaporative water losses. Supporting this, [23] reported that cover crops enhance water retention in the 10–18 cm soil layer, while [24] showed that oat–corn intercropping decreased water use by 4% and boosted yields by 23–42% compared to monocultures. In line with these studies, our results suggest that forage grasses promoted soil moisture conservation, which in turn favored greater biomass accumulation (Table 2).

Morphological traits of the forage cultivars also played an important role in productivity outcomes. BRS Zuri grass, although it forms dense clumps, maintains an upright growth habit that reduces competition with sorghum [25]. In contrast, Marandu grass—despite also having an upright stature—produces more prostrate and aggressive tillers, which intensify competition for light and space. These findings are consistent with [26], who observed that *Urochloa* spp. (particularly Marandu grass) impose strong competitive pressure during the early stages of sorghum development. Such physiological differences help explain the superior performance of Zuri-based intercropping systems in the present study (Table 2; Figure 3).

The productivity advantage of Zuri grass was most evident at wider spacings (Table 2, Figure 3), where its larger clump formation directly contributed to the outstanding total dry matter yield (TDMY) of the S + Z system. This advantage effectively offset minor reductions in sorghum dry matter yield (SDMY) and simultaneously provided substantial forage biomass for pasture establishment after harvest.

These findings highlight that, under the rainfed conditions of this study, sole sorghum cropping showed higher vulnerability to climatic variability compared to the intercropping systems. The association with Zuri grass, in particular, showed promising resilience, which may contribute to more stable productivity under water stress. However, confirming the robustness of these systems requires validation over multiple growing seasons to account for greater climatic variation.

4.2. Fermentative and Nutritional Parameters of Biomass Sorghum Silages

The high DMR (>93%) observed across all treatments demonstrates the efficiency of the ensiling process, with very limited losses. These results were even higher than those reported by [27] for biomass sorghum hybrids treated with microbial-enzymatic inoculants. DMR is an essential indicator of silage quality, as it represents the proportion of feed successfully preserved during storage.

Moreover, the absence of BA and the low NH_3-N concentrations (Table 2) provide clear evidence of restricted proteolysis and the lack of clostridial activity—both considered hallmarks of well-preserved silages [28,29]. Consistently, all silages maintained pH values below 4.0 (Table 2; Figure 3), a level regarded as optimal for sorghum silages [29]. Rapid pH decline following silo closure is crucial for silage stability, as it minimizes proteolysis, suppresses the growth of undesirable microorganisms, and ultimately enhances long-term preservation of fermentation quality.

The fermentation profile varied according to intercropping system and spacing. Reduced LA in S + M silages, especially at 45 cm, may be linked to interspecific competition delaying sorghum maturity and lowering WSC content, as previously reported by [30]. By contrast, intermediate LA levels in S + Z silages suggest that the competitive effect was less pronounced, allowing adequate lactic fermentation. In general, higher LA concentrations indicate a favorable fermentation profile, as they are directly associated with a rapid pH decline, which suppresses yeasts and *Clostridium* spp. [29].

A stable low pH also ensures greater silage stability during storage and feed-out, maintaining its quality for longer periods. In addition, LA is converted into propionic acid in the rumen, serving as an important energy source for animal production. Narrower spacings enhanced both LA and AA, likely due to greater WSC accumulation [28]. Importantly, BA was undetectable in all treatments and NH_3-N remained below the critical 10–15% TN threshold [29] (Table 2), confirming efficient fermentation. Biomass sorghum monoculture showed significantly lower dry matter content, though values were consistent with Ref. [27] for this hybrid.

Biomass sorghum cultivars generally have lower DM than other sorghum types due to their genetic background, which includes sweet sorghum in their breeding. These cultivars present juicier and more robust stalks, retaining more water and leading to higher effluent production [7]. Such characteristics reduce ensilability, as lower DM increases water activity and decreases soluble carbohydrate concentration [30]. Moreover, higher silage moisture favors the development of *Clostridium* spp., resulting in greater butyric acid and ammonia nitrogen production, which impairs silage nutritional quality [29]. Despite these effects, all treatments remained within the recommended DM range (Table 2) for silages [29].

While biomass sorghum monoculture at 90 cm spacing contained higher ash content, values remained below the 8% reported by [30]. Ash content has been proposed as an indirect marker to evaluate silage quality, since the mineral fraction is not degraded during the ensiling process, whereas the organic matter can be lost through fermentation, effluent, or gas production [30,31]. Thus, by comparing the ash content of the fresh forage with that of the silage after storage, it is possible to estimate organic matter losses indirectly.

However, caution is needed: when only the final ash contents of different silages are compared, little can be inferred. Higher ash values in the final product may reflect either greater organic matter losses during fermentation or simply a higher initial mineral concentration in the plant at harvest, influenced by cultivar, soil conditions, or climate [32]. Overall, the ash values observed in this study were low (Table 2) and consistent with those typically reported for sorghum silages.

Regarding CP, monoculture silages showed the highest concentrations, surpassing values reported for this hybrid in previous studies [27,33]. Nevertheless, the CP levels observed (8.66–9.10%; Table 2) are relatively low when compared to the nutritional requirements of beef and dairy cattle. According to [34], growing beef cattle typically require diets containing 12–14% CP, while finishing cattle still demand around 11–12%. For lactating dairy cows, requirements are even higher, ranging from 16–18% CP depending on milk yield [35]. Thus, although the CP content of sorghum silages contributes to the overall diet, it is insufficient to meet animal requirements when used as the only source, making protein concentrates essential to balance the diet. However, it is important to note that higher CP levels in silages can reduce the need for protein supplementation, thereby decreasing feeding costs and improving system efficiency.

Fiber fractions further distinguished treatments. NDF did not differ significantly (Table 2) but was numerically lower in intercropped silages (62.33–62.64% vs. 63.61%), suggesting potential for greater voluntary intake [36]. More importantly, ADF and lignin contents were consistently higher in monocultures, reflecting greater accumulation of structural carbohydrates due to advanced maturity at harvest. As ADF is negatively correlated with digestibility, intercropped silages presented higher energy availability, corroborated by greater TDN values (~60% in S + M and S + Z) compared to monocultures.

The TDN values also surpassed those reported by [32] in other hybrids and by [27,37] in the same hybrid, most likely due to differences in fiber composition. From a nutritional standpoint, higher TDN increases the energy density of the diet, which directly contributes to improved animal performance. In beef cattle, greater TDN levels are associated with higher average daily gain, as energy is the main limiting factor for tissue deposition [34]. For dairy cows, energy supply is equally critical, given that milk yield is strongly correlated with metabolizable energy intake. According to [35] each 1% increase in dietary TDN can result in an additional 0.2–0.3 kg of milk per cow per day. Therefore, differences of 2–3 percentage points among systems could translate into nearly 1 L of extra milk per cow daily, provided that protein availability is not limiting.

Other nutritional fractions also revealed relevant differences. Ether extract was higher in monocultures (Table 2), likely due to greater maturity at harvest. Lipids, when present at adequate levels (≤5%), can provide additional energy, reduce methane-related losses, and improve meat quality by increasing linoleic acid content [38,39]. The cutting and ensiling process may also release free fatty acids, further enriching forage nutritional value [40].

Digestibility results further confirmed the benefits of intercropping (Table 2; Figure 3). The highest NDFD48h was observed in S + M at 90 cm, likely due to delayed sorghum maturation caused by interspecific competition, which reduced lignification [33]. Although intercropping is often associated with increased CP [41], in this study it mainly favored starch accumulation, which also contributed to greater energy availability [36]. Taken together, the reduced fiber fractions, improved NDF digestibility, and higher TDN values in intercropped systems indicate a higher energy density compared to monocultures.

Overall, the nutritional profile of intercropped silages (Table 2; Figure 3)—characterized by adequate protein contribution, lower fiber contents, higher digestibility, and greater energy density—demonstrates their superior potential to sustain animal performance compared to biomass sorghum monoculture silage, which was limited by higher structural carbohydrate content and lower energy availability.

5. Conclusions

This study shows that intercropping biomass sorghum with tropical grasses is a viable strategy for integrated crop–livestock systems, enabling the production of high-quality silage while contributing to pasture recovery. The hypothesis of no yield or quality losses with simultaneous sowing was only valid for the sorghum-Zuri grass combination, as Marandu grass showed stronger competition, and 90 cm spacing proved more favorable than 45 cm. Overall, sorghum-Zuri grass at 90 cm spacing stood out by combining superior silage quality with the establishment of a vigorous pasture. Future studies should evaluate this intercropping system using other cultivars of *Urochloa* and *Megathyrsus* in different regions of Brazil to support broader and region-specific recommendations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriengineering7100345/s1, Figure S1: Variation in air temperature (maximum and minimum) and photosynthetically active radiation (PAR) over the crop growth season (November 2023 to March 2024).

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Abbreviations

The following abbreviations are used in this manuscript:

AA	Acetic Acid
ADF	Acid Detergent Fiber
BA	Butyric Acid
CLI	Crop–Livestock Integration
CP	Crude Protein
DM	Dry Matter
DMR	Dry Matter Recovery
EE	Ether Extract
FM	Fresh Matter
GDMY	Grass Dry Matter Yield
LA	Lactic Acid
LIG	Lignin
NDF	Neutral Detergent Fiber
NDFD48h	48 h in vitro Neutral Detergent Fiber Digestibility
NFC	Non-Fibrous Carbohydrates
NH_3-N	Ammonia Nitrogen
S + M	Sorghum intercropped with *Urochloa brizantha* cv. Marandu
S + Z	Sorghum intercropped with *Megathyrsus maximus* cv. Zuri
SDMY	Sorghum Dry Matter Yield
SEM	Standard Error of the Mean
TDMY	Total Dry Matter Yield
TDN	Total Digestible Nutrients
TN	Total Nitrogen

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