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Performance of Grain Sorghum and Forage of the Genus *Brachiaria* in Integrated Agricultural Production Systems

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Abstract: Forages of the genus *Brachiaria* stand out among those used in integrated systems. Little is known about the potential value of new species and cultivars when intercropped with sorghum and planted in the second crop season. The objective of this study was to evaluate the performance (agronomic characteristics) of grain sorghum and the production and nutritional characteristics of forage plants of the genus *Brachiaria* in an integrated agricultural production system in the second season. The experiment had a randomized block design with four replicates. The treatments consisted of the intercropping of sorghum with forage plants of the genus *Brachiaria* (Ruziziensis grass, Marandu, Xaraes, Piata, Paiaguas palisadegrass and Ipypora grass), in addition to an extra treatment with sorghum in monoculture. The results showed that sorghum intercropping with Ruziziensis grass, Paiaguas palisadegrass, Piata, and Ipypora grass did not cause a reduction in grain yield. The Xaraes, Piata, and Paiaguas palisadegrass showed higher forage production. However, the Paiaguas, Piata palisadegrass, and Ipypora grass showed better nutritional value. The sorghum intercropping with forage plants of the genus *Brachiaria* were promising alternatives for grain and forage production in the off-season. The right forage grass combined with sorghum in an integrated system can intensify agricultural production, optimizing the use of the area and increasing sustainability.

Keywords: *Brachiaria brizantha*; *Brachiaria ruziziensis*; crop–livestock integration; *Sorghum bicolor*; grain yield

1. Introduction

Encompassing 205 million hectares, the Cerrado region of Central Brazil has quickly become the main area of grain and meat production in the country [1]. According to the state-run National Supply Company [2], the production area and productivity of the region have increased by 1.8% compared to 2019.

The Brazilian scenario of agricultural expansion has generated economic returns to the country but also a large environmental liability [3]. Monocropping and inadequate soil and pasture management practices cause degradation and loss of natural resources, as well as reduced productivity and silting.

It is estimated that there are at least 32 million ha of degraded pastures in the Cerrado region of Brazil [4], i.e., areas characterized by a drop in the vigour of plant productivity. These areas have lower carrying capacity and animal production, which result in significant economic and environmental losses [5]. Thus, it is necessary to develop promotional actions such as the National Plan on Climate Change and the National Program for Low Carbon Agriculture [6].

In this context, crop–livestock integration systems have been considered one of the most sustainable and competitive technologies for the advancement of Brazilian agribusiness [7]. These systems prevent degradation and improve the use efficiency of agricultural areas [8,9], which have favoured their increasing adoption in Brazil [10]. In addition to their intensification and greater efficiency of land use, these systems generate other environmental benefits, such as increased carbon sequestration, increased soil organic matter, reduced erosion, and improved microclimatic conditions and animal welfare [11,12].

Due to the interactions between the annual crop and tropical forages, integrated systems become dynamic and complex, necessitating more accurate scientific and technological research to consolidate their environmental and production sustainability [13]. Several studies have shown the potential of including tropical forages in integrated systems for pasture diversification [8,14,15].

Grasses of the genus *Brachiaria* stand out among the forages used in intercropping systems in the Cerrado region. When included in integrated systems, this genus leads to improved soil structure due to its abundant root system [16], which favours soil aggregation [17] and water infiltration and improves aeration [18]. It also enables a lesser use of agrochemicals [19] and improves weed control [20], nutrient accumulation in the vegetation cover [21], and the production of quality forage in the food scarcity season (dry season), so it is able to meet the needs of ruminants [22].

Brachiaria ruziziensis was launched on the Brazilian market as a forage grass in the 1970s. In 1984, the cultivar Marandu was the most prominent, being considered the most cultivated species in the country [23]. After this period and following a long process of forage genetic improvement, the cultivar Xaraes was launched in 2004, followed shortly by the cultivars BRS Piata (2007), BRS Paiaguas (2013), and Ipypora, a hybrid (2017).

At the same time, alternative annual crops have emerged for use in integrated systems. Grain sorghum has been cultivated in the second crop season in the Central-West region of Brazil stands out [24]. This crop stands out for its lower soil fertility requirements, good resprouting ability after grain harvest, and greater tolerance to water deficit. These characteristics allow a greater range of sowing times, which is one of grain sorghum's greatest advantages over maize [25]. For these reasons, the cultivation of sorghum is increasingly expanding in Brazil, and the world production of grain [26], forage [27], and silage [15]. However, little is known about the potential of new forages of the genus *Brachiaria* intercropped with sorghum.

Therefore, and due to the need to generate more information about integrated systems, the objective of this study was to evaluate the performance (agronomic characteristics) of grain sorghum and the production and nutritional characteristics of forage plants of the genus *Brachiaria* in an integrated agricultural production system in the second season.

2. Materials and Methods

2.1. Experimental Site Description

This field experiment was conducted at an experimental site belonging to the Federal Institute of Goiano, located in the municipality of Rio Verde, Goias state, (17°48′ S; 50°55′ W; and 748 m altitude), on a typic Acriferric Red Latosol (according to the Brazilian soil classification [28].

Soil samples were collected to determine the physical-chemical characteristics of the soil in the experimental area at a 0–20 cm depth before the establishment of cultures with the following results: clay: 562 g kg^{-1}; silt: 94 g kg^{-1}; sand: 344 g kg^{-1}; hydrogen potential (pH) in calcium chloride ($CaCl_2$): 5.0; Calcium (Ca): 1.7; Magnesium (Mg): 1.1; Al: 0.0; Aluminum + Hydrogen (Al + H): 3.6;

Potassium oxide: 0.38; Cation exchange capacity (CEC): 6.78 $cmol_c$ dm^{-3}; Phosphor (Mehlich): 2.4; Cooper (Cu): 2.8; Zinc (Zn): 0.5; Iron (Fe): 16.1 in mg dm^{-3} and Organic matter (OM): 23.7 g kg^{-1}.

The relief of the region varies little, which helps explain the advance of mechanized and intensive agriculture [29]. The experimental site has a history of crop–livestock integration systems but had no agricultural activities in the last four years, and it contained many weeds.

The site was prepared by desiccation of the previous crop with the application of herbicide (Transorb 3.5 L ha^{-1}) at a dose of 2058 g ai ha^{-1} at a spray volume of 150 L ha^{-1}. Thirty days after desiccation, harrowing was performed with a harrow at 0.20 m depth to eliminate weeds not controlled by the herbicide, followed by a subsoiling and levelling.

The data on rainfall and monthly mean, minimum, and maximum temperatures during the experiment are shown in Figure 1. During the conduct of the research, there was enough rainfall for the crop development.

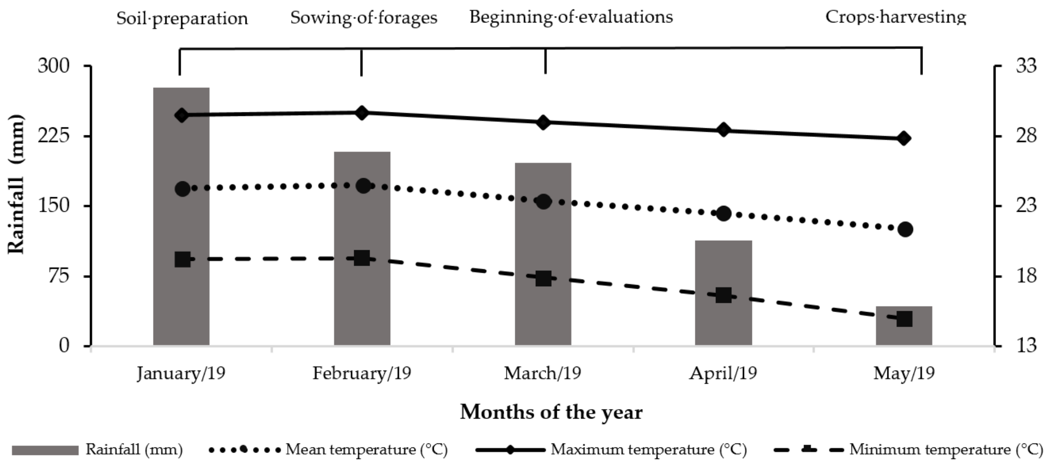

Figure 1. Precipitation values (mm), maximum temperature (°C), minimum temperature (°C), and average temperature (°C) in Rio Verde, Goias, Brazil, from January to May 2019.

2.2. Statistical Design, Treatments, and Crop Planting

The experiment was conducted in a randomized block design with four replicates. The treatments consisted of the intercropping of sorghum with forage plants of the genus *Brachiaria* (*Brachiaria ruziziensis*, *Brachiaria brizantha* cv. Marandu, *Brachiaria brizantha* cv. Xaraés, *Brachiaria brizantha* cv. BRS Piatã, *Brachiaria brizantha* cv. BRS Paiaguás, *Brachiaria* cv. BRS Ipyporã), in addition to an extra treatment comprising sorghum in monoculture. The grain sorghum hybrid used was Buster, a super-early phenotype with low stature and red grains and without tannin.

One week before sowing, 1 ton of lime filler was applied by broadcasting and was incorporated into the soil to increase the base saturation to 60%. The forage systems were sown manually on 4 February 2019, with the application of 200 kg ha^{-1} of P_2O_5 and 20 kg ha^{-1} of FTE BR 12 fertilizer (9% Zn, 1.8% B, 0.8% Cu, 2% Mn, 3.5% Fe, and 0.1% Mo), using simple superphosphate and fritted trace elements as sources, respectively.

In the monoculture and intercropping, sorghum was sown at 2 cm depth and the forage plants of the genus *Brachiaria* at 6 cm depth in the same sowing row. Each plot consisted of six 3.0-m-long rows spaced 0.50 m apart. The used area was only the three central rows, excluding 0.5 m from each end.

The sorghum sowing density was calculated to achieve an average population of 240,000 plants ha^{-1}. For forages of the genus *Brachiaria*, the equivalent of 5.0 kg of pure viable seeds per hectare. When the sorghum plants were at the three and six fully expanded leaf stages, two top-dressing fertilizations were performed, applying a total of 120 and 80 kg ha^{-1} of nitrogen and K_2O with urea and potassium chloride as sources, respectively.

For weed control post-emergence, weeding was performed weekly up to 50 days after sowing (DAS). Controls were performed for the fall armyworm (*Spodoptera frugiperda*) with two applications of 150 mL ha^{-1} of insecticide (lambda-cyhalothrin and chlorantraniliprole (7.5 and 15 g a.i ha^{-1}, respectively)) at 18 and 24 DAS.

2.3. Evaluation of Sorghum Agronomic Characteristics

The agronomic characteristics of the sorghum crop evaluated during its development were the plant height (measured from the ground to the end of the last fully expanded leaf or panicle) and stem diameter (at ground level) at 30 DAS (growth stage-GS 1: is characterized from germination to panicle differentiation), 60 DAS (growth stage-GS 2: from floral differentiation to flowering), 90 DAS (growth stage-GS 3: from flowering to physiological maturity of the grains). At harvest, all evaluations carried out on ten plants chosen at random in the useful area of the plots.

Sorghum was harvested on 20 May 2019 at 120 DAS. The panicle length (measurement of the length of ten panicles), panicle diameter (measured at the middle portion of the panicle), number of grains per panicle (grain threshing and subsequent counting), thousand-grain weight (weight of one thousand grains randomly selected after threshing, with 13% moisture correction) and grain yield (grain threshing and weight, with 13% moisture correction, converted to kg ha^{-1}).

2.4. Evaluation of Forage Plant Production and Nutritive Characteristics

The production characteristics of the forages were evaluated at 30, 60, and 90 DAS by measuring canopy height (measured from the plant base to the receptacle in 10 randomly selected plants) and number of tillers per m^2. After harvesting the sorghum, the canopy height, number of tillers, leaf blade:stem ratio, and dry mass production by cutting that simulated grazing, through manual cutting were also evaluated.

To determine the dry mass production, three 1-m linear samples were collected per plot by randomly placing a quadrat in each plot and cutting the Marandu, Xaraes, Piata, and Paiaguas palisadegrass at 20 cm from the soil and Ruziziensis and Ipypora grasses at 15 cm from the soil, contained within the quadrat. The material collected in the field was placed in plastic bags, sent to the laboratory, and weighed. Next, a representative sample was taken from each plot and dried in a forced-air oven at 55 °C to constant weight. Lastly, the samples were ground with a 1-mm screen and stored until analysis.

The variables were subjected to analysis of variance using R version R-3.1.1 (2014) with the ExpDes package [30]. The means were compared by Tukey's test at 5% probability.

3. Results

3.1. Sorghum Crop

Analysis of variance revealed significant effects ($p < 0.05$) of cropping system on plant height evaluated at 30 and 60 DAS. However, for the same variable at 90 DAS and stem diameter at 30, 60, and 90 DAS, there was no influence ($p > 0.05$) of cropping system, as the results were similar between treatments (Table 1).

Intercropping with the Marandu, Xaraes, Piata, and Paiaguas palisadegrass resulted in greater sorghum crop development, observed in sorghum height at 90 (Table 1). However, no differences ($p > 0.05$) were observed in height at 90 DAS (grain maturation stage (growth stage-GS3) or in stem diameter at any time.

At harvest, the final plant height was not influenced ($p > 0.05$) by cropping system (Table 2). In the final stem diameter and panicle diameter and length, only the intercropping with Xaraes palisadegrass differed ($p < 0.05$) from the other systems, showing the lowest value. For the number of grains per panicle, sorghum in monoculture and intercropped with the Ruziziensis and Ipypora grasses showed the highest values.

Table 1. Plant height and stem diameter in the vegetative stage (growth stage-GS1, 30 days after sowing (DAS)), reproductive stage (growth stage-GS2, 60 DAS), and grain maturation stage (growth stage-GS3, 90 DAS) of sorghum in monoculture and intercropped with forages of the genus *Brachiaria*.

Crop Systems	Stage 1	Stage 2	Stage 3
		Plant Height (cm)	
Sorghum in monoculture	50.8 b	91.8 b	100.9 a
Sorghum x Ruziziensis grass	53.7 ab	95.3 ab	100.5 a
Sorghum x Marandu palisadegrass	57.0 a	96.2 a	102.5 a
Sorghum x Xaraes palisadegrass	58.2 a	97.2 a	105.6 a
Sorghum x Piata palisadegrass	56.7 a	96.1 a	104.3 a
Sorghum x Paiaguas palisadegrass	57.8 a	96.4 a	101.7 a
Sorghum x Ipypora grass	53.0 ab	95.0 ab	101.9 a
SEM	1.08	0.800	2.50
		Stem Diameter (mm)	
Sorghum in monoculture	12.4 a	15.8 a	19.4 a
Sorghum x Ruziziensis grass	14.0 a	18.3 a	20.7 a
Sorghum x Marandu palisadegrass	14.1 a	18.4 a	20.4 a
Sorghum x Xaraes palisadegrass	13.9 a	17.6 a	20.6 a
Sorghum x Piata palisadegrass	13.8 a	17.2 a	19.8 a
Sorghum x Paiaguas palisadegrass	14.3 a	16.7 a	21.0 a
Sorghum x Ipypora grass	13.9 a	17.0 a	19.6 a
SEM	0.751	1.27	0.855

Means followed by different letters differ by Tukey's test at 5% probability. SEM—standard error of mean.

Table 2. Final plant height, final stem diameter, panicle diameter, panicle length, number of grains per panicle, thousand-grain weight, and grain yield of sorghum intercropped with forages of the genus *Brachiaria*.

Cropping System	Final Plant Height (cm)	Final Stem Diameter (mm)	Panicle Diameter (mm)
Sorghum in monoculture	103.5 a	21.4 a	57.5 a
Sorghum x Ruziziensis grass	107.9 a	21.7 a	58.4 a
Sorghum x Marandu palisadegrass	104.6 a	21.1 a	56.6 a
Sorghum x Xaraes palisadegrass	108.3 a	19.0 b	49.3 b
Sorghum x Piata palisadegrass	107.6 a	21.1 a	57.8 a
Sorghum x Paiaguas palisadegrass	106.8 a	21.7 a	56.2 a
Sorghum x Ipypora grass	104.6 a	21.2 ab	57.7 a
SEM	1.69	0.501	1.45
	Panicle Length (cm)	**N. Grains/Panicle**	
Sorghum in monoculture	26.5 a	251.9 a	
Sorghum x Ruziziensis grass	26.5 a	260.8 a	
Sorghum x Marandu palisadegrass	25.7 a	229.2 b	
Sorghum x Xaraes palisadegrass	22.7 b	222.4 b	
Sorghum x Piata palisadegrass	26.8 a	234.1 ab	
Sorghum x Paiaguas palisadegrass	26.1 a	239.9 ab	
Sorghum x Ipypora grass	26.8 a	254.3 a	
SEM	0.847	10.10	
	Thousand-Grain Weight (g)	**Grain Yield (kg ha^{-1})**	
Sorghum in monoculture	27.2 a	6129 a	
Sorghum x Ruziziensis grass	26.7 a	5935 a	
Sorghum x Marandu palisadegrass	21.1 b	5598 ab	
Sorghum x Xaraes palisadegrass	19.4 b	4918 b	
Sorghum x Piata palisadegrass	26.3 a	6121 a	
Sorghum x Paiaguas palisadegrass	26.2 a	6175 a	
Sorghum x Ipypora grass	27.6 a	5946 a	
SEM	1.16	200	

Means followed by different letters differ by the Tukey's test at 5% probability. SEM—standard error of mean.

Grain weight was lowest in the Xaraes, and Marandu palisadegrass intercropping, and grain yield was lowest only in the Xaraes palisadegrass. In addition to being lower than those obtained in the intercropping with Ruziziensis grass, Piata, Paiaguas palisadegrass, and Ipypora grass, the grain yield obtained in the Xaraes palisadegrass intercropping group was also lower than that obtained in the monoculture.

3.2. *Brachiaria Crop*

There was a significant effect ($p < 0.05$) of the cropping system on the production characteristics (canopy height, number of tillers, dry mass production, and leaf blade:stem ratio) of the forages (Table 3). The Ruziziensis and Ipypora grasses showed lower canopy height and number of tillers at 30, 60, and 90 DAS, differing of Xaraes, Piata, and Paiaguas palisadegrass.

Table 3. Canopy height and number of tillers of forages of the genus *Brachiaria* intercropped with grain sorghum, evaluated at 30, 60, and 90 days after sowing (DAS).

Cropping System	30 DAS	60 DAS	90 DAS
	Canopy Height (cm)		
Sorghum x Ruziziensis grass	36.2 c	81.8 c	95.4 c
Sorghum x Marandu palisadegrass	46.4 ab	96.3 ab	105.9 ab
Sorghum x Xaraes palisadegrass	55.5 a	108.4 a	115.5 a
Sorghum x Piata palisadegrass	42.1 b	91.2 b	100.7 b
Sorghum x Paiaguas palisadegrass	43.8 b	92.0 b	101.5 b
Sorghum x Ipypora grass	35.1 c	74.6 c	93.5 c
SEM	1.97	2.74	5.13
	Number of Tillers (m^2)		
Sorghum x Ruziziensis grass	69.3 b	99.6 b	204.6 b
Sorghum x Marandu palisadegrass	71.0 b	107.3 b	207.0 b
Sorghum x Xaraes palisadegrass	86.0 a	115.0 a	240.0 a
Sorghum x Piata palisadegrass	81.6 a	113.0 a	235.0 a
Sorghum x Paiaguas palisadegrass	83.3 a	116.7 a	234.6 a
Sorghum x Ipypora grass	66.6 b	102.0 b	209.6 b
SEM	6.64	4.54	15.37

Means followed by different letters differ by the Tukey's test at 5% probability. SEM—standard error of mean.

The canopy height of the forages evaluated at harvest and the dry mass production were highest in the Xaraes palisadegrass, followed by Marandu, Piata, and Paiaguas palisadegrass, which all ad higher values ($p < 0.05$) than the *B.* Ruziziensis and Ipyporã grasses, that showed smaller heights (Table 4). The Piata, and Paiaguas palisadegrass showed a higher leaf blade:stem ratio, at 34% higher than the mean of the Ruziziensis grass, Marandu, Xaraes palisadegrass, and Ipypora grass. Furthermore, for the number of tillers, Ruziziensis grass, Marandu palisadegrass, and Ipypora grass showed lower values (Table 4).

Table 4. Canopy height, dry mass production, leaf blade:stem ratio and number of tillers of *Brachiaria* forages intercropped of the *Brachiaria* intercropped with sorghum, evaluated at harvest.

Crop Systems	Canopy Height (cm)	DM Production (kg ha^{-1})	Leaf Blade:Stem Ratio	Number of Tillers (m^2)
Sorghum x Ruziziensis grass	103.3 c	3860 c	1.8 b	264.6 b
Sorghum x Marandu palisadegrass	132.0 ab	4160 b	1.9 b	260.0 b
Sorghum x Xaraes palisadegrass	143.3 a	6270 a	1.7 b	306.6 a
Sorghum x Piata palisadegrass	133.0 ab	4600 ab	2.4 a	288.0 a
Sorghum x Paiaguas palisadegrass	137.3 ab	5230 ab	2.6 a	305.3 a
Sorghum x Ipypora	109.6 c	4040 c	2.0 b	256.6 b
SEM	4.53	0.215	0.128	11.07

Means followed by different letters differ by the Tukey's test at 5% probability. SEM—standard error of mean.

There was a significant effect ($p < 0.05$) of cropping system on forage quality (crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), lignin, and in vitro dry mass digestibility

(IVDMD) (Table 5). The Piata, Paiaguas palisadegrass, and Ipypora grass presented higher CP ($p < 0.05$) than the other forages, which had similar values (Table 5).

Table 5. CP, NDF, ADF, lignin, and IVDMD (g kg^{-1} DM) contents of forages of the genus *Brachiaria* intercropped with grain sorghum, evaluated at harvest.

Crop Systems	CP	NDF	ADF	Lignina	IVDMD
Sorghum x Ruziziensis grass	91.9 b	723.6 b	422.0 b	275.3 b	550.4 b
Sorghum x Marandu palisadegrass	108.8 b	729.0 b	428.5 b	282.6 b	571.0 b
Sorghum x Xaraes palisadegrass	107.7 b	735.8 a	440.5 a	373.3 a	583.5 ab
Sorghum x Piata palisadegrass	123.0 a	717.4 b	418.8 b	247.0 b	603.5 a
Sorghum x Paiaguas palisadegrass	125.1 a	713.5 b	418.7 b	248.6 b	604.4 a
Sorghum x Ipypora grass	121.6 a	718.7 b	420.8 b	268.0 b	603.7 a
SEM	0.717	0.613	0.563	0.252	1.47

Means followed by different letters differ by Tukey's test at 5% probability. DM: dry matter; CP: crude protein; NDF: neutral detergent fibre; ADF: acid detergent fibre; IVDMD: in vitro dry matter digestibility. SEM—standard error of mean.

The highest values of the fibrous fractions NDF, ADF, and lignin were obtained with the Xaraes palisadegrass, which differed from the other forages. As for IVDMD, the Piata, Paiaguas palisadegrass, and Ipypora grass had the highest digestibility values (Table 5).

4. Discussion

4.1. Sorghum Crop

The taller height of the sorghum plants intercropped with Marandu, Xaraes, Piata, and Paiaguas palisadegrass is due to the greater etiolation of sorghum. This is attributed to the greater competition for light and physical space, resulting in greater stem elongation in the first two evaluations (GS1 and GS2). At these stages, especially in the second, sorghum plants are undergoing intense vegetative development [31]. These findings demonstrate the ability of sorghum to adapt to the amount of solar radiation incident on its leaves [32].

The greater competition displayed by sorghum when intercropped with Marandu, Xaraes, Piata, and Paiaguas palisadegrass is also attributed to the morphological characteristics of the grasses. Because they have erect and cespitose growth, in addition to being tall [33], these forages drive greater competition in the initial development stage of sorghum plants. However, at 90 DAS, the sorghum plants overcame the interference caused by intercropping, as observed by the lack of significant differences in plant height. Similar results were obtained by [34–37] when they intercropped sorghum with Xaraes, Marandu, Piata palisadegrass, Decumbens, Ruziziensis grasses and Paiaguas palisadegrass.

The lower values observed for final stem diameter and panicle diameter and length of sorghum intercropped with Xaraes palisadegrass are explained by the morphological characteristics of the forage species: It is the tallest, even exceeding the height of some sorghum plants. This forage also has large leaves, large clumps, and a deep root system and is more aggressive in seeking water and nutrients for growth [33]. Combined with the planting of both species in the same sowing row, these factors made for greater competition with the sorghum, thus reducing the latter's final stem diameter, as also observed by [38] with the same forage grass. Stem diameter is one of the main morphological structures for storage of reserve substances in plants. The larger the diameter, the greater the photoassimilate storage capacity, which contributes to grain formation [39].

Intercropping with Ruziziensis and Ipypora grasses did not affect the number of grains per panicle compared to monoculture. These results may be related to the smaller size of these forages, which contributed to the lesser competition between the crops. The panicle length and number of grains per panicle directly influence the grain yield [40], as the greater the panicle length and weight are, i.e., the more grains there are, the greater the yield will be [36]. The fact that sorghum has longer panicles led to a higher number of grains and thousand-grain weight, as reported [38]. This led to lesser effects of these forages on sorghum at the maturation stage.

The reduction in sorghum thousand-grain weight and yield when intercropped with Marandu and Xaraes palisadegrass can also be explained by the larger size of these forages than Ruziziensis grass, Piata, Paiaguas palisadegrass, and Ipypora grass. One of the premises of integrated systems is the complementation of the production of both crops, without affecting overall productivity. Thus, the presence of Xaraes palisadegrass caused competition to the point of decreasing productivity, showing that this is not the most suitable forage for integrated systems with grain sorghum.

In turn, the association of sorghum with Ruziziensis grass, Piata, Paiaguas palisadegrass, and Ipypora grass may be a viable technique for intercropping because it did not lower the grain yield, and the same area could be used for grain and forage production. In addition to this benefit of the system, it improves the biological, chemical [41], and physical [17] soil attributes and the efficiency of nutrient cycling [21], as well as helping with cost reduction [42], diversification, maintenance of income from the property [43], and the use of the same arable area with higher yield, compared to the conventional system [14].

Due to the differences in the study regions and genetics, in addition to the time of implementation of the system, grain yields in the present study were lower than reported by [44], higher than reported by [26,36] and [45] similar to those reported by [26] for intercropping of grain sorghum with *Brachiaria* species in the second crop season for grain and biomass production.

Thus, intercropping with forage grasses is a promising cultivation alternative. In addition to the grain production by the crop, the forages can be used for animal feeding in the off-season. Later, biomass is produced for soil cover for the no-tillage system of the next crop season.

4.2. Brachiaria Crop

Canopy height at 30, 60, and 90 DAS was highest in the Xaraes palisadegrass, followed by Marandu palisadegrass, due to the morphology of these forages: They are taller [46] and engage in less competition [33] than the Piata, Paiaguas palisadegrass [47], Ruziziensis, and Ipypora grasses.

Sorghum germination is faster when compared to forage from the genus *Brachiaria*, which can take up to 15 days more to germinate. In addition, there was an influence of the depth of sowing, where the sorghum was sown at 2 cm and the forages at 6 cm, favoring a faster germination. Thus, in intercropping, sorghum exerts a shading effect on the forage plants. This causes etiolation, which can affect dry mass production. Competition for light promotes stem elongation, stimulating leaf growth to capture light in the upper part of the canopy [48]. Thus, the change in the structure of the forage plant may lead to less leaf accumulation, decreasing the leaf blade:stem ratio. This can negatively affect the nutritional value of the forage. Variations in the canopy height of forages when intercropped with sorghum in the second crop season for grain and biomass production were also reported by [26].

The higher number of tillers obtained in the Xaraes, Piata, and Paiaguas palisadegrass at 30, 60, and 90 DAS was due to the better development of these forages, contributed to greater plant heights at sorghum harvest and to greater dry mass production.

When pearl millet (*Pennisetum glaucum* (L.) *R. Br.*) was intercropped with Paiaguas palisadegrass [22], sowing pear millet did not hinder the development of Paiaguas palisadegrass in the row or interrow since there was no competition for resources. The same was seen by [49] in maize (*Zea mays*) intercropped with Ruziziensis grass. These results were confirmed in the present study for the Marandu, Xaraes, Piata, and Paiaguas palisadegrass.

The smallest forage productions of the Ruziziensis and Ipypora grasses were attributed to the morphology of these forages, which have small clumps, high basal tillering, low emission of stolons and thin and short stems [50,51].

All forages achieved satisfactory dry mass production, ranging from 3860 to 6270 kg ha^{-1} (Ruziziensis grass and Xaraes palisadegrass, respectively). This result is relevant because forage production in the off-season is of paramount importance, as there is low forage availability during this period, impairing animal performance. These results are similar to those observed by [22] and [14], who evaluated the intercropping of pearl millet and maize with Paiaguas palisadegrass in the second crop season and found forage production above 5000 kg ha^{-1}. These authors opined that intercropping is a promising cultivation technique for grain production and that after harvest, forage with good nutritional value is available to be used in the off-season.

Forage production in intercropping was highest for Xaraes palisadegrass. Another study [52] found higher forage production by Xaraes palisadegrass compared to Ruziziensis grass and Marandu palisadegrass, as did [53] compared to Piata palisadegrass. Thus, intercropping was found to be a promising cultivation technique for the production of grain and forage to be used in the off-season. The advantage of using the integrated system for these purposes is that after the grain crop is harvested, the area can be used for animal grazing in the off-season. A better-quality pasture with integrated systems at that time of year, when forage availability is typically low, allows greater livestock exploitation in the off-season [54].

The land-use intensification and crop diversification of integrated systems are noteworthy, as the land is kept producing throughout the year. This is possible with soybean cultivation in the first crop season (summer) followed by corn or sorghum intercropped with forage for grain production (second crop season). After harvesting the cereal, it is possible to produce forage by forage species for animal feeding in the dry season [55].

Benefits of perennial grasses in crop–livestock integration systems are reported in the literature. Over the years of cultivation, forages promote positive changes in soil chemical and physical attributes [56]. Additionally, the dual role of forage species in intercropping allows not only the production of high-quality and high-quantity forage during the fall–winter period but also the provision of mulch for the sustainability of the no-tillage system [54]. This cultivation modality allowed the inclusion of new forage species adapted to intercropping, as well as the possibility of expanding this cultivation system with other crops.

Regarding forage quality, the higher leaf blade:stem ratio of Piata and Paiaguas palisadegrass is associated with the morphology of these forages, which have thin stems with a large proportion of leaves [47].

This allowed us to obtain higher CP, which is one of the great advantages of these forages. The mean CP content of the Piata, Paiaguas palisadegrass, and Ipypora grass was 124.0 g kg^{-1} DM, 20% higher than the mean of Ruziziensis grass, Marandu, and Xaraes palisadegrass. These results are relevant when selecting the appropriate forage to provide better-quality forage in the off-season. In general, the forages had CP above 70 g kg^{-1} DM, meeting the protein requirements and not limiting the microbial growth of ruminal cellulolytic bacteria [57]. Emphasis should be given to the Piata, Paiaguas palisadegrass, and Ipypora grass, which are important alternative forages for animal production systems due to their forage quality (49-51-47). The CP contents obtained in this study were similar to those found by [58] with Marandu, Xaraes, Piata, MG-4 palisadegrass, Decumbens, and Ruziziensis grasses and by [59] with Marandu, Piata, and Xaraes palisadegrass.

The higher NDF, ADF, and lignin contents in Xaraes palisadegrass are explained by the numbers of stems and clumps (fibrous fractions) that this forage presents [33]. The NDF contents ranged from 719 to 736 g kg^{-1} DM (Ipypora grass and Xaraes palisadegrass, respectively), similar to the values in another study on intercropping of annual crops with tropical forages [58]. The ADF contents were similar to those obtained by [14] with the use of Paiaguas palisadegrass in an integrated system with corn. Due to its higher proportion of fibrous fractions, especially stems, Xaraes palisadegrass had a higher lignin content (37 g kg^{-1} DM), which is the nondigestible fraction of the plant.

The higher IVDMD found in the Piata, Paiaguas palisadegrass, and Ipypora grass is related to their higher leaf blade:stem ratio, higher CP content, and lower fibrous fractions content. These make carbohydrates easily digestible for rumen microorganisms [60], resulting in better digestibility. Higher NDF and ADF cause lower forage intake and digestibility, thus impairing animal performance [61]. Similar results were obtained by [52] with *Brachiaria brizantha* cultivars (Marandu, Piata, and Xaraes), which indicates that Xaraes palisadegrass had the lowest CP and digestibility among the forages evaluated.

Integrated systems are important for providing high-quality forage in the off-season, a time of low forage quality due to the seasonality of production [55]. Typically, at this time of year, protein supplementation is provided to animals due to the low quality of the forage. However, when integrated systems are used, after harvesting the annual crop, the pasture becomes available to animals in the form of quality forage, so supplementation is unnecessary. It is important to note that this is possible in pastures established in the first year of crop-livestock integration.

5. Conclusions

The sorghum intercropping with Ruziziensis grass, Paiaguas palisadegrass, Piata, e Ipypora grass did not cause a reduction in grain yield in the crop year.

The Xaraes, Piata, and Paiaguas palisadegrass showed higher forage production. However, the Paiaguas, Piata palisadegrass, and Ipypora grass showed better nutritional value.

The sorghum intercropping with forage plants of the genus *Brachiaria* was a promising alternative for grain and forage production in the off-season. The right forage grass combined with sorghum in an integrated system can intensify agricultural production, optimizing the use of the area and increasing sustainability.

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