

GOIANO FEDERAL INSTITUTE OF EDUCATION, SCIENCE AND
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POSTGRADUATE PROGRAM IN ANIMAL SCIENCE

**INTERCROPPING MAIZE WITH *Panicum maximum* AND
Stylosanthes CULTIVARS IMPROVES SILAGE PRODUCTION
AND QUALITY IN INTEGRATED SYSTEMS**

Author: Wildo Pereira Matos
Advisor: Prof^a. Dra. Kátia Aparecida de Pinho Costa
Co-advisor: Prof. Dr. Adriano Carvalho Costa

Rio Verde - GO
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LIST OF SYMBOLS, ABBREVIATIONS, AND UNITS.

%	Percentage
CH ₄	Methane Gas
EE	Ether Extract
EM	Metabolizable Energy
FB	Crude Fiber
FDA	Acid Detergent Fiber
FDN	Neutral Detergent Fiber
g	Grams
g kg ⁻¹	Grams per kilogram
kg	Kilogram
ha	Hectares
°C	Degrees Celsius
m	Meter
cm	Centimeters
mm	Millimeters
m ²	Square Meters
N	Nitrogen
K	Potassium
K ₂ O	Potassium Chloride
P ₂ O ₅	Phosphorus Pentoxide
Mg	Magnesium
MS	Dry Matter
PB	Crude Protein
pH	Potential of Hydrogen
NDT	Total Digestible Nutrients
N-NH ₃	Ammoniacal Nitrogen
NH ₃	Ammonia

ABSTRACT

MATOS, WILDO PEREIRA. Goiano Federal Institute of Education, Science and Technology - Rio Verde Campus, February 2026. **Maize intercropping with *Panicum maximum* and *Stylosanthes* cultivars improved silage production and quality in integrated systems.** Advisor: Prof. Dr. Kátia Aparecida de Pinho Costa, Co-advisor: Prof. Dr. Adriano Carvalho Costa.

The adoption of silage production strategies focused on improving quality, combined with environmental conservation, is essential to ensure the production sustainability and the best use of resources. This study aimed to evaluate the effect of triple intercropping of Maize, *Panicum maximum* cultivars, and *Stylosanthes* on dry matter production, fermentation profile, and nutritional value of silages, compared to monoculture of these crops. The experiment was carried out in the field, in a randomized block design, with nine treatments and three replications. The following silage treatments were evaluated: Maize monoculture; tamani grass monoculture; Quenia guinea grass monoculture; *Stylosanthes* cv. Bela monoculture; *Stylosanthes* cv. Campo Grande monoculture; Maize intercropped with Tamani grass and Bela; Maize intercropped with tamani grass and Campo Grande; Maize intercropped with Quenia guinea grass and Bela; and Maize intercropped with Quenia guinea grass and Campo Grande. The results showed that the intercropping increased silage mass production and improved fermentative characteristics, with reductions of 10.91%; 25.03%; 37.43%; 33.94% and 26.68% in pH, buffering capacity, ammoniacal nitrogen, total dry matter losses and effluent production, respectively, compared to silages of *Panicum maximum* and *Stylosanthes* cultivars in monoculture. Furthermore, there was a 26.10% increase in crude protein content compared to Maize silage. Among the *Stylosanthes* cultivars, Bela showed the greatest intercropping capacity. Regarding the *Panicum maximum* cultivars, both can be recommended for intercropping. It is concluded that the Maize system with *Panicum maximum* and *Stylosanthes* cultivars can be recommended for silage production, focusing on sustainability and reducing costs with mineral fertilization.

Keywords: Forage conservation; triple intercropping; legumes; sustainability.

RESUMO

MATOS, WILDO PEEIRA. Instituto Federal de Educação, Ciência e Tecnologia de Goiás – Campus Rio Verde, fevereiro de 2026. **Consórcio de milho com cultivares de *Panicum maximum* e *Stylosanthes* melhora a produção e a qualidade da silagem em sistemas integrados.** Orientadora: Prof^a. Dr^a. Kátia Aparecida de Pinho Costa, Coorientador: Prof. Dr. Adriano Carvalho Costa.

A adoção de estratégias de produção de silagem visando à melhoria da qualidade, juntamente com a conservação ambiental, é essencial para garantir a sustentabilidade da produção e uma melhor utilização dos recursos. Este estudo foi conduzido com o objetivo de avaliar o efeito do consórcio triplo de milho, cultivares de *Panicum maximum* e *Stylosanthes* sobre a produção de matéria seca, o perfil fermentativo e o valor nutritivo das silagens, em comparação ao monocultivo dessas espécies. O experimento foi realizado em campo, em delineamento de blocos ao acaso, com nove tratamentos e três repetições. Foram avaliados os tratamentos de silagem de: milho em monocultivo; capim-guiné Tamani em monocultivo; Capim-guiné do Quênia em monocultura; Bela em monocultura; Campo Grande em monocultura; milho consorciado com capim-guiné Tamani e Bela; milho consorciado com capim-guiné Tamani e Campo Grande; milho consorciado com capim-guiné do Quênia e Bela; e milho consorciado com capim-guiné do Quênia e Campo Grande. Os resultados mostraram que o consórcio aumentou a produção de silagem de massa seca e melhorou as características de fermentação, reduzindo em 10,91%; 25,03%; 37,43%; 33,94% e 26,68% o pH, a capacidade tamponante, o nitrogênio amoniacal, as perdas totais de matéria seca e a produção de efluentes, respectivamente, em comparação com as silagens de cultivares de *Panicum* e *Stylosanthes* em monocultura. Além disso, aumentou o teor de proteína bruta em 26,10% em comparação com a silagem de milho. Entre os cultivares de *Stylosanthes*, o cultivar Bela apresentou a maior capacidade de consórcio. Em relação aos cultivares de *Panicum maximum*, ambos podem ser recomendados para consórcio. Conclui-se que um sistema de cultivo de milho com cultivares de *Panicum maximum* e *Stylosanthes* pode ser recomendado para a produção de silagem, com foco na sustentabilidade e na redução dos custos associados à fertilização mineral.

Palavras-chave: Conservação de forragem; consórcio triplo; leguminosas; sustentabilidade.

1. GENERAL INTRODUCTION

After the 1960s, there were important changes in the eating habits of the world's population, significantly increasing per capita meat consumption (Gu et al., 2019). This factor is mainly related to population growth, people's purchasing power, and the increasing urbanization process, which could reach an estimated 9.15 billion people by 2050 (Titei et al., 2022; Costa Júnior et al., 2025). This resulted in an increased demand for animal protein, leading to the use of 240 million hectares dedicated to feed production of feed for ruminants. This number could double by 2030 if other alternatives are not created (Gu et al., 2019).

Extractive livestock farming is still considered one of the biggest contributors to global warming due to the production of greenhouse gases, especially methane (CH₄), resulting from the enteric digestion process of ruminants (Ramírez-Restrepo et al., 2020). Cattle grazing is the most practical and economical way to feed livestock in tropical regions. However, the yield obtained in these extensive systems is very low, a fact mainly attributed to the irregularity in forage supply throughout the seasons (Rufino et al., 2022).

The need to develop economic alternatives to mitigate greenhouse gas emissions is indispensable in order to maintain production processes capable of meeting global market demand, while promoting environmental sustainability (Beauchemin et al., 2020). In this context, integrated agricultural and livestock systems have stood out in recent years as a sustainable and competitive practice to meet global demand and boost the development of the agricultural sector (Dias et al., 2020).

Intercropping is a type of integrated planting that uses two or more species in the same area simultaneously (Buhk et al., 2017). This system increases land use efficiency (Prado et al., 2023), stabilizes productivity, and improves soil health (Silva et al., 2025b) by combining species with complementary growth habits and nutritional needs, optimizing the use of resources such as light, water, and nutrients (Folina et al., 2025). Therefore, diversified cropping systems increase ecological stability, contribute to biodiversity conservation, and provide farmers with multiple sources of income and food security (Fan et al., 2025).

Research conducted in different contexts has shown that silage production in integrated systems represents an efficient alternative to promote productive intensification in a sustainable way in tropical environments (Denardin et al., 2025). When a tropical perennial grass is included in the Maize intercropping system, it has advantages such as better acceptance by animals (Khan et al., 2015) and subsequent pasture formation (Souza et al., 2025). In addition,

when legumes are included in the system, there is an increase in the crude protein content of the silage (Silva et al., 2024; Marques et al., 2025). Together, this inclusion represents an alternative for producer to reduce the cost of acquiring mineral fertilizers, due to the biological fixation of nitrogen in the soil through legumes (Silva et al., 2025a).

Despite the associated benefits, crop intercropping involves limitations that require careful evaluation (Wang et al., 2023). Its effective adoption depends on proper planning and management, since inadequate choices can compromise the system's performance (Leal et al., 2023). Therefore, the choice of forage genetic resources to compose the diversified cropping model is fundamental to meeting the needs of sustainable ecosystems while improving the efficiency and quality of agricultural production (Fan et al., 2025).

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3. OBJECTIVES

3.1. General objective

To evaluate dry matter production, fermentation profile, and nutritive value of maize silage, Tamani guinea grass, Quenia guinea grass, Bela stylo, and Campo Grande in monocropped and triple intercropped systems.

3.2. Specific objectives

To evaluate dry matter production of maize, Tamani guinea grass, Quenia guinea grass, Bela stylo, and Campo Grande in monocropped and triple intercropped systems.

To determine the fermentation profile of maize silage, Tamani guinea grass, Quenia guinea grass, Bela stylo, and Campo Grande in monocropped and triple intercropped systems.

To determine the chemical-bromatological composition of maize silage, Tamani guinea grass, Quenia guinea grass, Bela, and Campo Grande in monocropped and triple intercropped systems.

CHAPTER 1

(Article under review *International Journal of Agronomy*)

Intercropping of maize with cultivars *Panicum maximum* and *Stylosanthes* improves silage production and quality in integrated systems

Abstract

The adoption of silage production strategies aimed at improving quality, along with environmental conservation, is essential to ensure the production sustainability and better resource utilization. This study examined the impact of the triple intercropping system of maize, *Panicum maximum* and *Stylosanthes* cultivars on dry matter yield, fermentation profile, and nutritive value of silages in relation to monocropping systems. The experiment was carried out in the field, using a randomized block design with three replications. We evaluated the treatments: silage from maize in monocropped; Tamani guinea grass in monocropped; Quenia guinea grass in monocropped; Bela in monocropped; Campo Grande in monocropped; maize intercropped with Tamani guinea grass and Bela; maize intercropped with Tamani guinea grass and Campo Grande; maize intercropped with Quenia guinea grass and Bela; and maize intercropped with Quenia guinea grass and Campo Grande. The results showed that intercropping increased production of dry mass silage and improved fermentation characteristics, reducing by 10.91%; 25.03%; 37.43%; 33.94% and 26.68% in pH, buffering capacity, ammoniacal nitrogen, total dry matter losses, and effluent production, respectively, compared to silages of cultivars *Panicum* and *Stylosanthes* monocropped. In addition, it increased crude protein content in 26.10% compared to maize silage. Among the *Stylosanthes* cultivars, the Bela cultivar showed the greatest capacity for intercropping. Regarding the *Panicum maximum* cultivars, both can be recommended for intercropping. It is concluded that the Maize system with *Panicum maximum* and *Stylosanthes* cultivars can be recommended for silage production, focusing on sustainability and reducing costs associated with mineral fertilization. **Keywords:** Forage conservation; triple intercropping; legumes; sustainability

1. Introduction

The growing global demand for more sustainable agricultural production systems, driven by an increasing and more demanding world population, requires efforts to find solutions that synergize environmental regeneration and agricultural production (Zhao et al., 2024). This involves reducing the use of inorganic inputs and increasing the adoption of new practices that promote the integration, conservation, and regeneration of resources, ensuring production diversification and agricultural resilience (Wies et al., 2023).

Among these practices, integrated systems stand out as a sustainable intensification practice, as they diversify the production of plant species in the same area, whether in space-time, simultaneously or separately, and in rotation or succession, generating synergistic effects (Chakraborty et al., 2024). When properly managed, these systems promote beneficial interactions between crops, improving soil health (Camargo et al., 2024; Silva et al., 2024a), reducing the vulnerability of plantations to market and climate risks (Fernandes et al., 2023; Meunier et al., 2024), and decreasing the presence of invasive plants (Mello et al., 2023). In addition, they promote pasture recovery (Damian et al., 2023), silage production (Prado et al., 2023), and serve to reduce costs with the purchase of concentrates during the dry season (Silva et al., 2024b).

In this context, silage production from integrated systems has been considered a promising strategy with satisfactory results, increasing silage biomass production per unit area, in addition to improving the nutritional value of the silage (Vicente et al., 2023). Additionally, in recent years, studies have shown that the inclusion of legumes in maize intercropping systems with forage grasses not only improves the quantity and quality of silage (Prado et al., 2023; Silva et al., 2024b), but also enhances all other elements of the system, generating greater nutrient cycling, which reduces dependence on mineral fertilizers (Silva et al., 2025), resulting in better land use efficiency (Pariz et al., 2020). Therefore, this system has the potential to provide ecosystem services while increasing yields, making triple intercropping a promising practice for food production (Zhao et al., 2024; Silva et al., 2024b).

Although several crops have been suggested as raw material for silage production, maize is considered the standard crop (Mosebi et al., 2024). However, its crude protein content ranges from 60 to 90 g kg⁻¹ of dry matter (Silva et al., 2023c). In addition, studies have shown that continuous monocropped can deplete soil nutrients, increase pests and diseases, and lead to a decline in crop productivity (Renard and Tilman, 2021). In this context, intercropped maize with tropical forages such as grasses of the *Panicum maximum* genus stands out due to their

high dry matter yield per unit area (Herrera et al., 2023), adaptability to different climatic conditions (Fernandes et al., 2023), and their ability to maintain productivity and diversify farm income (Li et al., 2024).

When combined with legumes, the agricultural system is further enriched, as the system benefits from species complementarity, resulting in increased crop productivity (Silva et al., 2021) and silage quality (Prado et al., 2023), reducing the use of synthetic nitrogen (N) fertilizers due to the symbiotic relationship with soil bacteria (rhizobia), which facilitate biological nitrogen fixation (BNF). This contributes to the reduction of greenhouse gas emissions (Jensen et al., 2020). Among tropical forage legumes, *Stylosanthes* stand out by its adaptation to low-fertility soils and ability to fix up to 120 kg of nitrogen ha⁻¹ year⁻¹ (Epifanio et al., 2019).

Thus, this study examined the impact of the triplon intercropped of maize, *Panicum maximum* and *Stylosanthes* cultivars on dry matter yield, fermentation profile, and nutritive value of silages in relation to monocropped of these crops. The hypothesis is that the triple intercropped can increase the production of dry mass for ensilage, improve the fermentative characteristics of silages from *Panicum* and *Stylosanthes* cultivars in monocropped and improve quality, with higher protein content, thus contributing to a more efficient and sustainable production system.

2. Materials and Methods

2.1 Description of the Area and Crop Establishment

The experiment was carried out in the experimental area of the Instituto Federal Goiano, Rio Verde Campus (under the coordinates 17°48' S, 50°54' W, and altitude of 832 m, Rio Verde, State of Goiás, Brazil). The soil is classified as a Latossolo Vermelho Acriférico típico (Santos et al., 2018), Oxisol in the USA Keys of Soil Taxonomy (Soil Survey Staff, 2014), with a clayey texture (562 g kg⁻¹ of clay). The experimental area has a history of more than ten years of adoption of the crop-livestock integration system.

Soil samples were collected from the 0.0–0.20 m layer, in October 2022, prior to the establishment of the experiment for chemical characterization. The soil presented a pH in CaCl₂ of 5.3; calcium (Ca): 2.60 cmol_c dm⁻³; magnesium (Mg): 1.40 cmol_c dm⁻³; aluminum (Al): 0.01 cmol_c dm⁻³; hydrogen (H) + Al: 4.40 cmol_c dm⁻³; potassium (K): 0.65 cmol_c dm⁻³; cation exchange capacity (CEC): 9.05 cmol_c dm⁻³; current base saturation of the soil (V1): 51.3%; phosphorus (P) (Mehlich-1): 4.8 mg dm⁻³; sulfur (S): 8.3 mg dm⁻³; copper (Cu): 3.5 mg dm⁻³; zinc (Zn): 1.0 mg dm⁻³; iron (Fe): 17 mg dm⁻³; and organic matter (OM): 27.8 g dm⁻³.

The region's climate is tropical (Aw), characterized by a dry season in winter and a rainy season in summer, according to the Köppen-Geiger classification (Cardoso et al., 2014). During the experiment, rainfall distribution was considered normal for the period, totalling 1,483 mm, with an average maximum temperature of 29.68 °C, an average temperature of 23.66 °C, and an average minimum temperature of 17.64 °C (Figure 1).

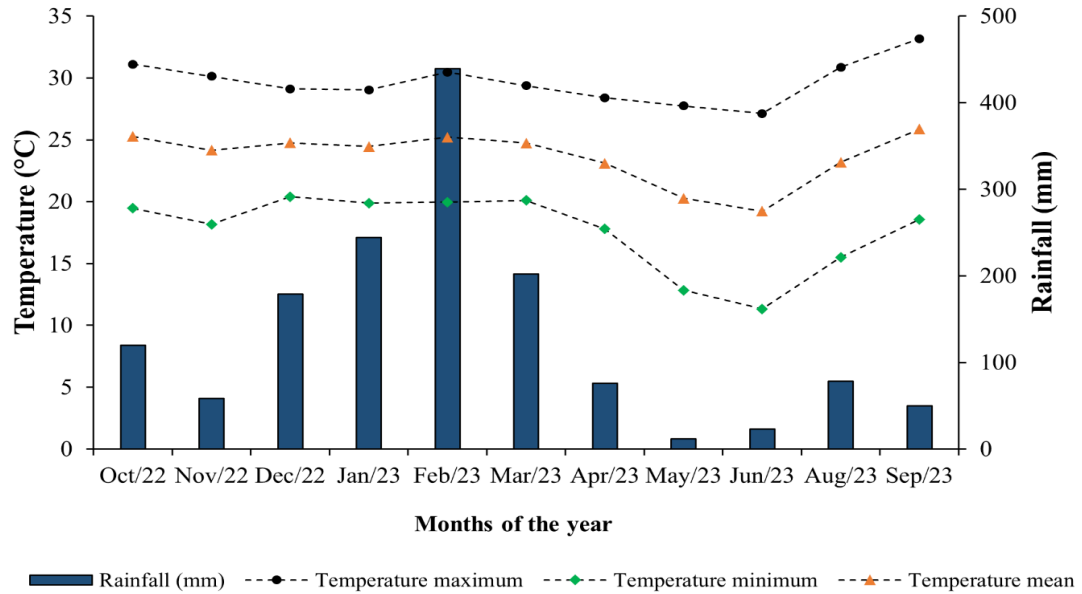


Figure 1. Monthly rainfall and minimum, average, and maximum temperatures recorded from October 2022 and to September 2023.

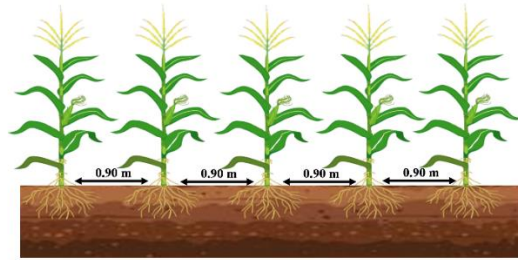
2.2 Experimental design and treatments

A randomized complete block design with three replications was used as the experimental design. Nine treatments were evaluated, including silage from maize (*Zea mays* L.) monocropped; Tamani guinea grass (*Panicum maximum* cv. BRS Tamani) monocropped; Quenia guinea grass (*Panicum maximum* cv. BRS Quênia) monocropped; Bela (*Stylosanthes guianensis* cv. Bela) monocropped; Campo Grande (*Stylosanthes* cv. Campo Grande) monocropped; maize with Tamani guinea grass and Bela, maize with Tamani guinea grass and Campo Grande, maize with Quenia guinea grass and Bela, and maize with Quenia guinea grass and Campo Grande. The maize hybrid used was P4285.

The procedures for establishment and experimental management followed methodology previously described in the literature (Silva et al., 2024b; Silva et al., 2025). Each experimental plot had a total area of 21.6 m². In the monocropped systems, the crops were sown with a row spacing of 0.90 m. In the intercropping systems, maize was sown with a row spacing of 0.90

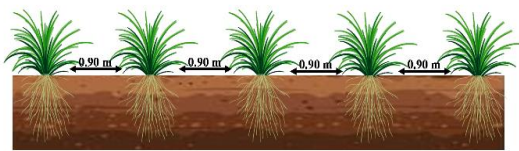
m, while the forage grasses and legumes were sown at 0.30 m from the maize rows. All crops were sown at a depth of 0.03 m (Figure 2).

(a)



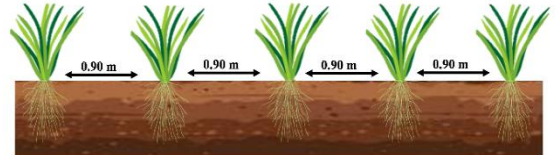
Maize (*Zea mays* L. hybrid P4285)

(b)



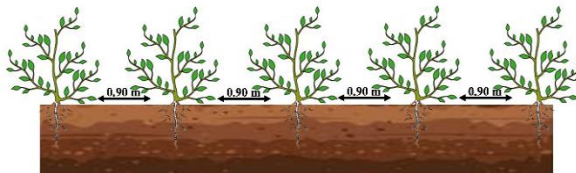
Tamani guinea grass (*Panicum maximum*)

(c)



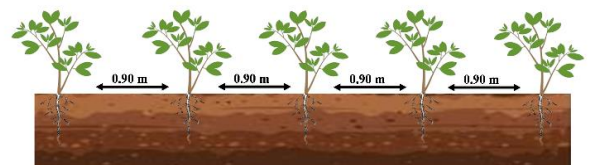
Quenia guinea grass (*Panicum maximum*)

(d)



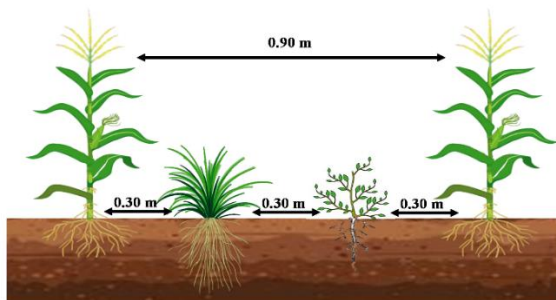
Bela (*Stylosanthes guianensis*)

(e)



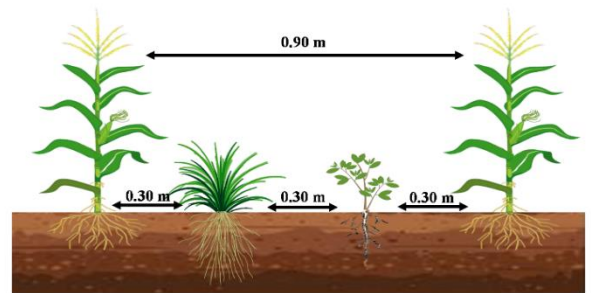
Campo Grande (*Stylosanthes guianensis*)

(f)



Maize intercropped with Tamani guinea grass and Bela

(g)



Maize intercropped with Tamani guinea grass and Campo Grande

(h)

(i)

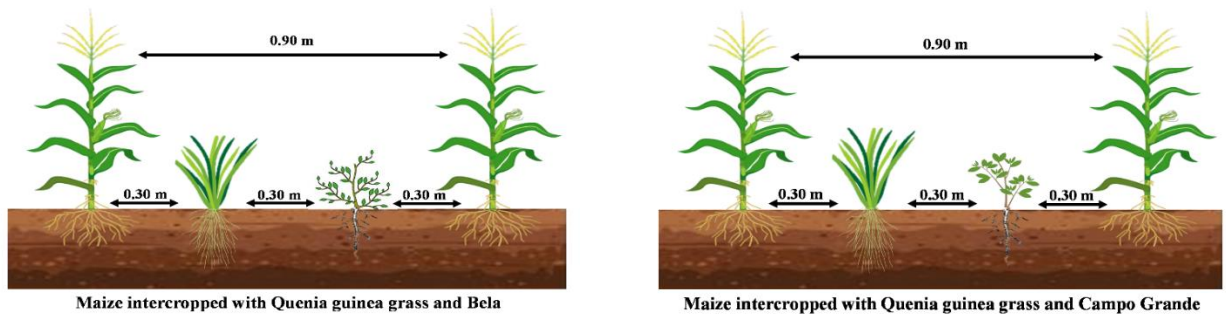


Figure 2. Crops arrangement: maize monocropped (a), Tamani guinea grass monocropped (b), Quenia guinea grass monocropped (c), *Stylosanthes guianensis* cv. Bela monocropped (d), *Stylosanthes* cv. Campo Grande monocropped (e), maize intercropped with Tamani guinea and Bela (f), maize intercropped with Tamani guinea grass and Campo Grande (g), maize intercropped with Quenia guinea grass and Bela (h), and maize intercropped with Quenia guinea grass and Campo Grande (i).

At the time of sowing, 100 kg ha⁻¹ of P₂O₅ and 20 kg ha⁻¹ of FTE BR 12 (containing 9% zinc, 1.8% boron, 0.8% copper, 2% manganese, 3.5% iron, and 0.1% molybdenum) were applied in the planting furrow, using single superphosphate and Fritas as the respective sources. A sowing density of five maize seeds per linear meter was used. For cultivars *Panicum maximum* BRS Tamani and Quenia guinea grasses, 3 kg ha⁻¹ of seeds (78% of cultural value) was used, while 6.0 kg ha⁻¹ of *Stylosanthes guianensis* cv. Bela seeds (35% of cultural value) and 5.0 kg ha⁻¹ of *Stylosanthes* cv. Campo Grande seeds (40% of cultural value) were used. These sowing rates were applied to both monocropped and intercropped systems.

Topdressing fertilization was carried out at two stages, when maize reached the phenological stages of three and six fully developed leaves. In total, 150 kg ha⁻¹ of N and 80 kg ha⁻¹ K₂O were applied to the monocropped maize and grass plots, using urea as the nitrogen source and potassium chloride as the potassium source. In the intercropped treatments, half the nitrogen dose (75 kg ha⁻¹) was applied, aiming to take advantage of biological nitrogen fixation promoted by the *Stylosanthes* plants, along with 80 kg ha⁻¹ of K₂O. In the *Stylosanthes* monocropped, only 80 kg ha⁻¹ of K₂O was applied.

The control of *Spodoptera frugiperda* and *Dalbulus maidis* was carried out using a knapsack sprayer at the beginning of maize development, with a 20-day interval between applications. The insecticides Klorpan and Connect were used at doses of 0.4 L ha⁻¹ and 0.1 L ha⁻¹ of commercial product, respectively.

2.3 Silage of the crops

At 98 days after sowing (DAS), on June 2, 2023, the crops were manually harvested for ensilage at 0.20 m above the soil surface, when maize was at the dough grain stage, presenting approximately 336.45 g kg⁻¹ of dry matter (DM). To determine the proportion of ensiled material (Table 1), the crops were harvested and weighed separately to establish the proportion of maize, forages, and legumes in each treatment. To determine dry matter production, a portion of the harvested material was taken to an oven for 72 h at 55 °C, where dry weight was determined and the results were converted to kg ha⁻¹.

Table 1. Proportion of material ensiled from maize, Tamani guinea grass, Quenia guinea grass, *Stylosanthes guianensis* cv. Bela and *Stylosanthes* cv. Campo Grande in monocropped and intercropped.

Cultivation system	Proportion of ensiled material (%)		
	M	G	L
Maize monocropped	100	0	0
Tamani guinea grass monocropped	0	100	0
Quenia guinea grass monocropped	0	100	0
Bela monocropped	0	0	100
Campo Grande monocropped	0	0	100
Milho + Tamani guinea grass + Bela	71.66	15.45	12.89
Milho + Tamani guinea grass + Campo Grande	76.31	16.45	7.24
Milho + Quenia guinea grass + Bela	67.79	20.02	12.20
Milho + Quenia guinea grass + Campo Grande	71.93	21.24	6.83

M: maize; G: grasses (Tamani e Quenia guinea grasses); L: legumes (*Stylosanthes* Bela and Campo Grande).

After harvest, the fresh material was chopped into particles of approximately 10 mm using a forage grinder. It was then ensiled in experimental PVC silos measuring 0.10 m in diameter and 0.40 m in length. The material was manually compacted using a wooden pendulum, and the silos were sealed with PVC lids and adhesive tape to prevent air entry. The silos were stored in a protected location at ambient temperature.

A sample of approximately 0.5 kg of the chopped fresh material (before ensiling), was collected and dried in an oven at 55°C until constant weight for chemical-bromatological analyses, where dry matter (DM), crude protein (CP), lignin, and ether extract (EE) were determined following the methods described by AOAC (1990). According to Mertens (2002),

neutral detergent fiber (NDF) and acid detergent fiber (ADF) were determined. Total digestible nutrients (TDN) content was calculated based on the equation proposed by Chandler (1990). According to Tilley and Terry (1963), *in vitro* dry matter digestibility (IVDMD) was evaluated, adapted to the artificial rumen system developed by ANKON®, using the “Daisy incubator” equipment from Ankom Technology (*in vitro* true digestibility – IVTD). The results of these analyses are presented in Table 2.

Table 2. Bromatological characteristics (g kg⁻¹ dry matter) of maize, Tamani guinea grass, Quenia guinea grass, *Stylosanthes guianensis* cv. Bela and *Stylosanthes* cv. Campo Grande in monocropped and intercropped before ensiling.

Cultivation system	DM	CP	EE	IVDMD
Maize monocropped	336.45	71.94	39.98	698.70
Tamani guinea grass monocropped	266.60	112.03	20.04	581.84
Quenia guinea grass monocropped	275.18	110.14	20.13	575.68
Bela monocropped	268.12	155.22	22.04	629.41
Campo Grande monocropped	261.10	154.52	22.14	630.47
Milho + Tamani guinea grass + Bela	311.63	130.82	30.37	648.37
Milho + Tamani guinea grass + Campo Grande	302.09	121.99	30.85	660.71
Milho + Quenia guinea grass + Bela	316.21	129.12	30.75	636.62
Milho + Quenia guinea grass + Campo Grande	312.76	122.07	31.27	659.04
	NDF	ADF	lignin	TDN
Maize monocropped	532.73	295.96	29.76	662.54
Tamani guinea grass monocropped	684.97	390.15	56.36	586.62
Quenia guinea grass monocropped	696.62	400.95	57.39	579.70
Bela monocropped	614.95	355.41	30.81	588.75
Campo Grande monocropped	619.21	343.33	30.26	579.65
Milho + Tamani guinea grass + Bela	624.52	361.96	39.92	614.12
Milho + Tamani guinea grass + Campo Grande	619.62	353.29	37.37	633.38
Milho + Quenia guinea grass + Bela	627.43	377.03	41.95	619.15
Milho + Quenia guinea grass + Campo Grande	616.12	350.25	39.38	630.32

DM: dry matter; CP: crude protein; EE: ether extract; IVDMD: *in vitro* dry matter digestibility; NDF: neutral detergent fiber; ADF: acid detergent fiber; TDN: total digestible nutrients.

2.4 Opening of silos and analyses of fermentative and bromatological characteristics of the silage

After 55 days of fermentation, the silos were opened, and the upper and lower portions of each silo were discarded. The central portion was placed in trays. A sample of the silage was used to perform analyses of the fermentative characteristics, according to Silva and Queiroz (2022), namely: pH, buffering capacity, and ammoniacal nitrogen (N-NH₃).

To avoid variations in the results, pH and buffering capacity were determined immediately after silo opening. Ammoniacal nitrogen was determined only after freezing the samples, to reduce the activity of anaerobic bacteria and prevent nitrogen volatilization.

Total dry matter losses were calculated by the difference between the initial and final gross weights of the silos, corrected for the dry matter contents of the material before ensiling and after silo opening (Jobim et al., 2007). Effluent production was calculated by the difference between the initial and final gross weights of the silos, corrected for the amount of fresh forage mass ensiled (Jobim et al., 2007). Organic acids, such as lactic acid and acetic acid, were quantified using a high-performance liquid chromatography (HPLC), coupled with an ultraviolet (UV) detector at 210 nm wavelength, following the technique described by Kung and Shaver (2001).

Another portion of the material, approximately 0.5 kg, was dried in a forced-air ventilation oven at 55 °C until constant weight. Subsequently, the samples were ground using a 1 mm sieve and stored in plastic containers for later analysis of the chemical-bromatological characteristics of the silage, applying the same methodology used for the fresh material. The analyses were performed between August and October 2023.

2.5 Statistical analysis

The variables were subjected to analysis of variance (ANOVA) using the R software (version R-3.1.1, R Core Team, 2014), with the ExpDes package (Ferreira et al., 2014). Means were compared by Tukey's test at a 5% significance level ($p < 0.05$).

Correlations between variables were calculated using Pearson's linear correlation coefficient. Subsequently, the Student's t-test was applied to verify the significance of the correlations. Principal component analysis (PCA) was performed using the computational packages "tidyverse," "stats," and "factoextra" in the R software, version R-3.1.1 (R Core Team, 2014).

3. Results

3.1 Dry matter production

One of the main advantages of integrated systems is the increased production of biomass for ensiling due to the simultaneous growth of multiple crops in the same area. This was confirmed in our study, where the highest dry matter production was observed in the triple intercropping of Maize + Quenia guinea grass + Bela (24,424 kg ha⁻¹), followed by the intercropping of Maize + Quenia guinea grass + Campo Grande and Maize + Tamani guinea grass + Bela, which did not differ significantly from each other (average of 23,069 kg ha⁻¹), and lastly the intercropping Maize + Tamani guinea grass + Campo Grande (21,705 kg ha⁻¹), representing increases of 32.21%, 28.20%, and 23.69%, respectively, compared to maize monocropped (Figure 3). Dry matter production of Quenia guinea grass was 27% higher compared to Tamani guinea grass. Meanwhile, Bela monocropped provided 47.2% greater dry matter production compared to Campo Grande monocropped, which showed the lowest production (1571.9 kg ha⁻¹).

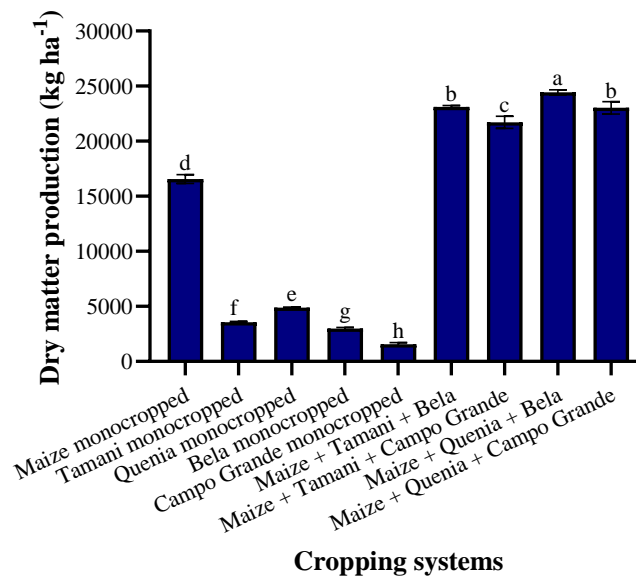


Figure 3. Dry matter production of the ensiled material from maize, Tamani guinea grass, Quenia guinea grass, *Stylosanthes guianensis* cv. Bela and *Stylosanthes* cv. Campo Grande in monocropped and intercropped.

Means followed by different letters differ by Tukey's test ($p < 0.05$).

Vertical bars represent the standard error of the mean.

3.2 Fermentative Characteristics

The different cropping systems significantly influenced ($p < 0.05$) the fermentative characteristics (pH, buffering capacity, and N-NH₃) and dry matter content of the silages (Figure 4). The highest pH values were observed in the silages of Bela and Campo Grande in monocropped systems (4.46 and 4.50, respectively). Silages from intercropped systems showed a 10.91% reduction in pH compared to *Stylosanthes* silages in monocropped. Maize silage in monocropped exhibited the lowest pH, with 3.75 (Figure 4a).

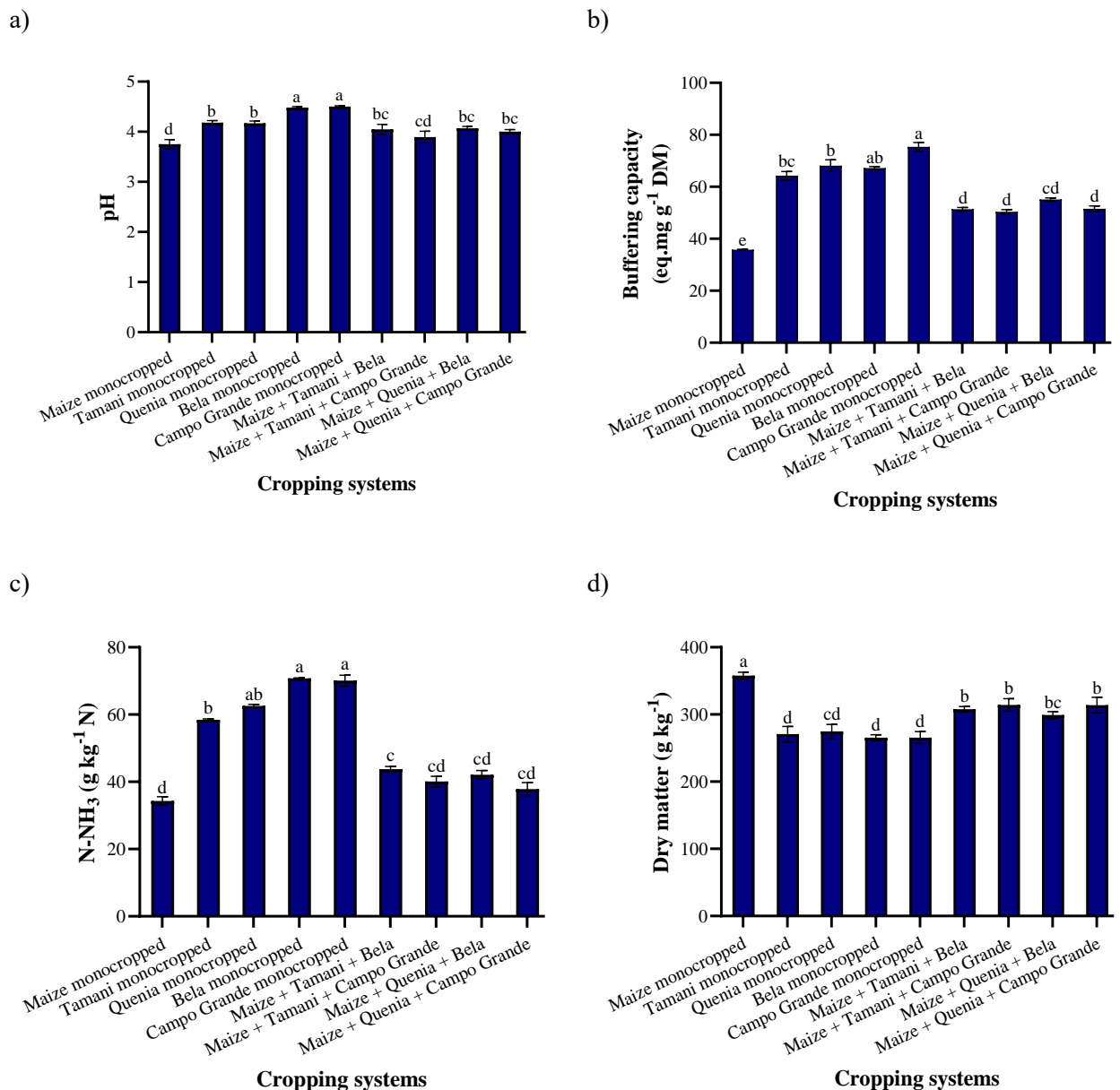


Figure 4. Contents of pH (a), buffering capacity (b), N-NH₃ (c), and dry matter (d) of silage from maize, Tamani guinea grass, Quenia guinea grass, *Stylosanthes guianensis* cv. Bela and *Stylosanthes* cv. Campo Grande in monocropped and intercropped.

Means followed by different letters differ by Tukey's test ($p < 0.05$).

Vertical bars represent the standard deviation.

The *Stylosanthes* silages in monocropped showed the highest buffering capacity and N-NH₃ levels, followed by Tamani and Quenia guinea grasses (Figures 4b and 4c). The intercropped systems were effective in reducing buffering capacity by 25.03% and N-NH₃ by 37.43% compared to the silages from monocropped systems. The lowest buffering capacity and N-NH₃ (35.79 eq.mg g⁻¹ DM and 34.29 g kg⁻¹ N, respectively), values were observed in maize silage in monocropped.

For the dry matter (DM) contents of the different cropping systems (Figure 4d), the monocropped maize silage showed the highest value (357.7 g kg⁻¹). The intercropped systems resulted in a 12.78% increase in DM contents compared to the monocropped of cultivars *Panicum maximum* and *Stylosanthes*, which showed the lowest values (average of 269.2 g kg⁻¹).

The highest total DM losses were observed in the silages of cultivars *Panicum maximum* and *Stylosanthes* grown in monocropped (average of 27.2 g kg⁻¹). In contrast, there was a reduction in losses of 27.90% in the silages from intercropping systems with *Stylosanthes guianensis* cv. Bela (Maize + Tamani guinea grass + Bela and Maize + Quenia guinea grass + Bela), and 39.99% for the silages from the intercropping systems with *Stylosanthes* cv. Campo Grande (Maize + Tamani guinea grass + Campo Grande and Maize + Quenia guinea grass + Campo Grande). Maize silage under monocropped conditions showed 11.3 g kg⁻¹ of total dry matter loss, being the lowest (Figure 5a).

The highest effluent productions were observed in the silages of cultivars *Stylosanthes* monocropped (Figure 5b), followed by the silages of cultivars *Panicum maximum* monocropped. The monocropped maize silage showed the lowest effluent production. Intercropped systems were effective in reducing effluent production by 26.68% compared to the silages of cultivars *Panicum* and *Stylosanthes* monocropped (Figure 5b).

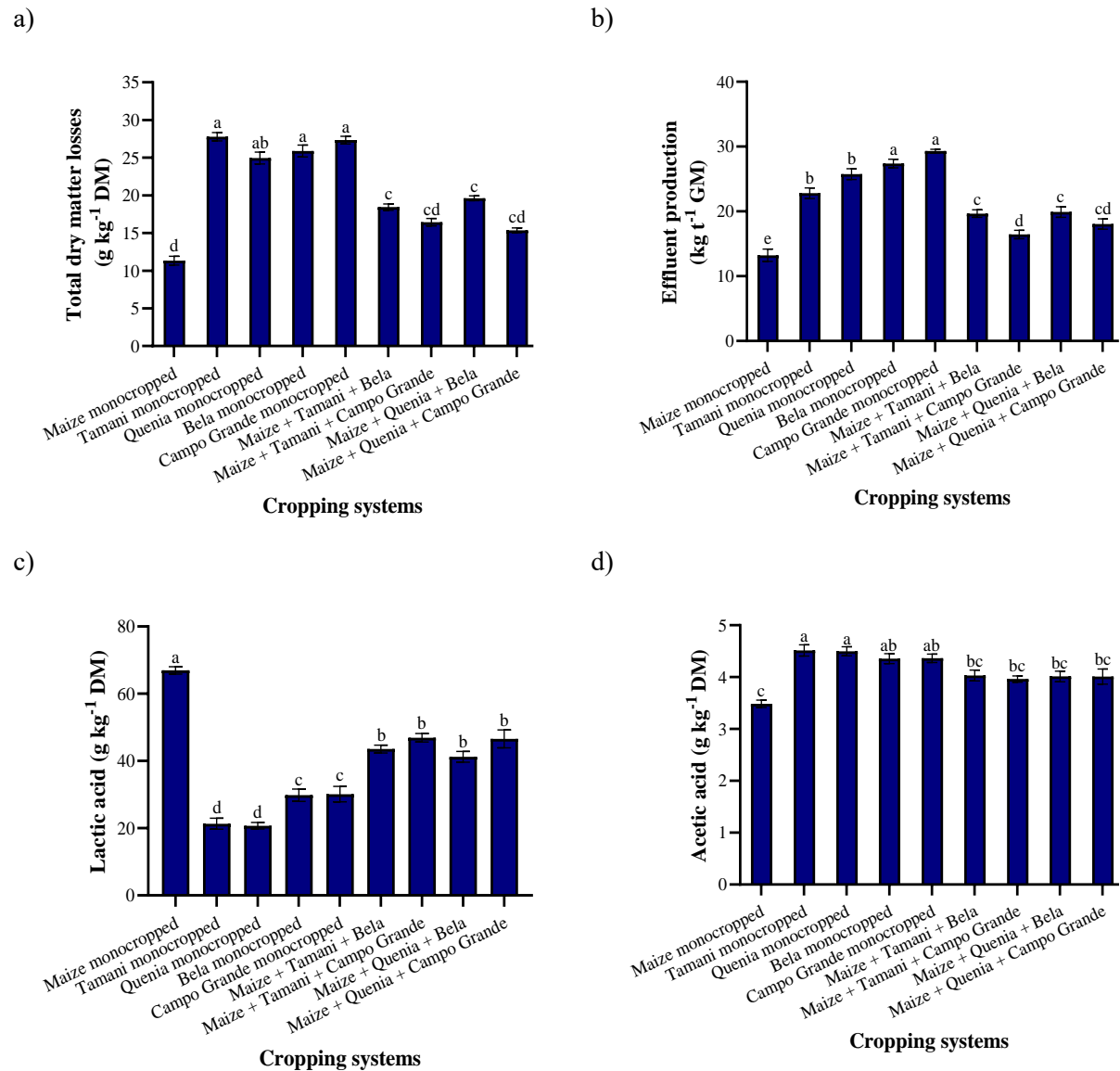


Figure 5. Total dry matter losses (a), effluent production (b), lactic acid (c), and acetic acid (d) contents in silage from maize, Tamani guinea grass, Quenia guinea grass, *Stylosanthes guianensis* cv. Bela and *Stylosanthes* cv. Campo Grande in monocropped and intercropped. Means followed by different letters differ by Tukey's test ($p < 0.05$). Vertical bars represent the standard deviation of the mean.

For lactic acid, the highest concentration was observed in the silage of maize monocropped ($66.9 \text{ g kg}^{-1} \text{ DM}$), followed by the intercropped systems (average of $44.5 \text{ g kg}^{-1} \text{ DM}$), which proved to be effective in increasing lactic acid production by 32.76% and 52.85% compared to the silages of cultivars *Stylosanthes* and *Panicum maximum* monocropped, respectively. In contrast, the maize monocropped silage had the lowest acetic acid concentration ($3.48 \text{ g kg}^{-1} \text{ DM}$). The intercropped systems were effective in reducing acetic acid production

by 8.27% and 11.22% compared to the silages of cultivars *Stylosanthes* and *Panicum maximum* monocropped, respectively, which had the highest levels of this acid.

3.3 Bromatological Characteristics

The bromatological characteristics (crude protein, neutral detergent fiber (NDF), acid detergent fiber (ADF), lignin, *in vitro* dry matter digestibility (IVDMD), ether extract, and total digestible nutrients (TDN) were significantly influenced ($p < 0.05$) by the different cropping systems (Figures 6 and 7). The highest crude protein content (average of $145.1 \text{ g kg}^{-1} \text{ DM}$) was found in the silages of Campo Grande and *Bela* in monocropped. The silages of Tamani and Quenia guinea grasses and the intercropped systems showed intermediate values. The intercropped systems showed the potential to increase crude protein content by 26.10% compared to the maize silage in monocropped (Figure 6a).

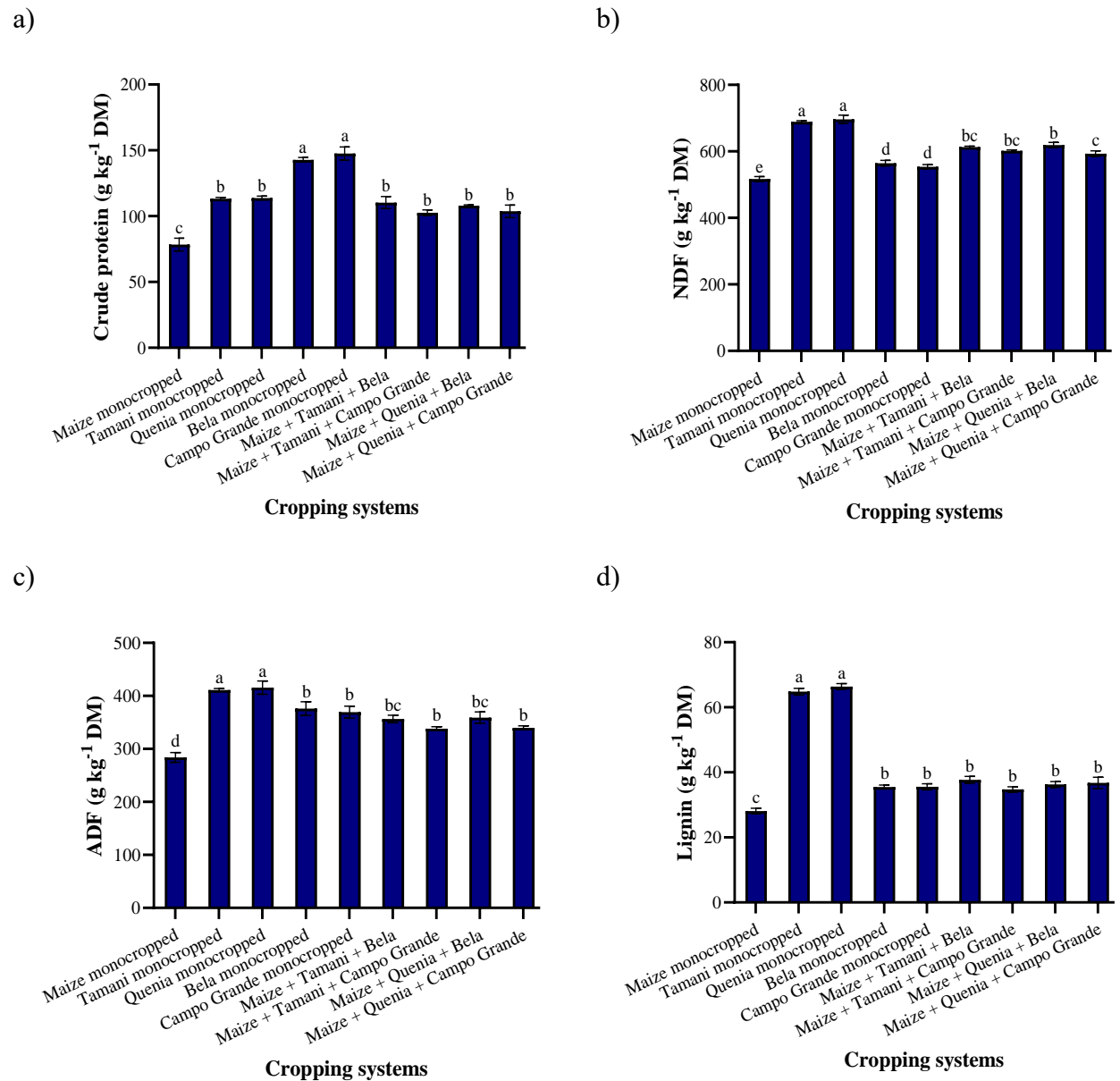


Figure 6. Contents of crude protein (a), neutral detergent fiber (NDF) (b), acid detergent fiber (ADF) (c), and lignin (d) of the silage of maize, Tamani guinea grass, Quenia guinea grass, *Stylosanthes guianensis* cv. Bela and *Stylosanthes* cv. Campo Grande in monocropped and intercropped.

Means followed by different letters differ by Tukey's test ($p < 0.05$).

Vertical bars represent the standard deviation of the mean.

For the contents of NDF, ADF, and lignin, a similar pattern was observed, with the lowest values (516.7, 283.9, and 28.1 g kg⁻¹ DM, respectively) found in the maize silage in monocropped (Figures 6b, 6c, and 6d). The silages of Tamani and Quenia guinea grasses in monocropped showed the highest fiber fractions. The silages of *Stylosanthes* in monocropped

and the intercropped systems presented intermediate results, with reductions of 14.70%, 13.76%, and 44.97% in NDF, ADF, and lignin, respectively, compared to the silages of cultivars *Panicum* in monocropped.

The intercropping systems were effective in increasing the *in vitro* dry matter digestibility (IVDMD) of cultivars *Stylosanthes* and *Panicum maximum* silages in monocropped systems by 3.64% and 9.76%, respectively. The maize silage in monocropped system showed the highest IVDMD ($684.9 \text{ g kg}^{-1} \text{ DM}$) (Figure 7a).

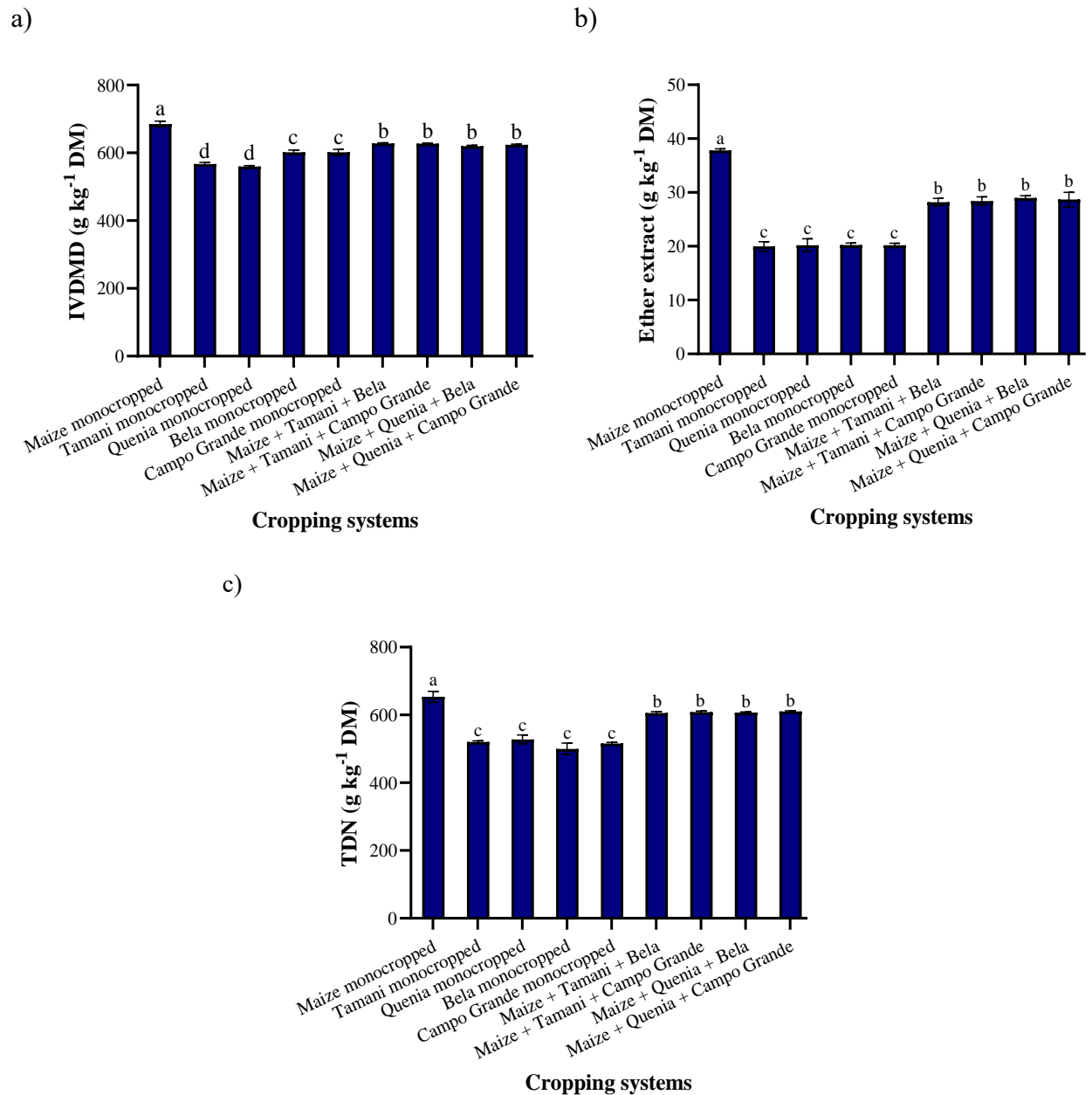


Figure 7. *In vitro* dry matter digestibility (IVDMD) (a), ether extract (EE) (b), and total digestible nutrients (TDN) (c) of silage from maize, Tamani guinea grass, Quenia guinea grass,

Stylosanthes guianensis cv. Bela and *Stylosanthes* cv. Campo Grande in monocropped and intercropped.

Means followed by different letters differ by Tukey's test ($p < 0.05$).

Vertical bars represent the standard error of the mean.

For ether extract (EE) and total digestible nutrients (TDN) contents, similar results were observed, with the highest values (37.8 e 653.4 g kg⁻¹ DM, respectively), in the silage of maize in the monocropped system. The intercropped systems showed a potential increase of 29.94% and 15.13% in EE and TDN contents, respectively, compared to the silages of tropical forage grasses in monocropped systems, which exhibited the lowest values (average of 20.1 and 515.8 g kg⁻¹ DM, respectively) (Figures 7b and 7c).

3.4 Multivariate Analysis

The correlation analysis (Figure 8) showed that two variable groups were formed, with group 1 consisted of TDN, DM, EE, Lactic, and IVDMD while group 2 was composed of CP, pH, N-NH₃, Effluent, Buffering, MM, TDML, ADF, Acetic, Lignin, and NDF. Variables within the same group exhibited positive correlations, while variables between different groups showed negative correlations. Only NDF showed no significant correlation with CP, pH, N-NH₃, and Effluent.

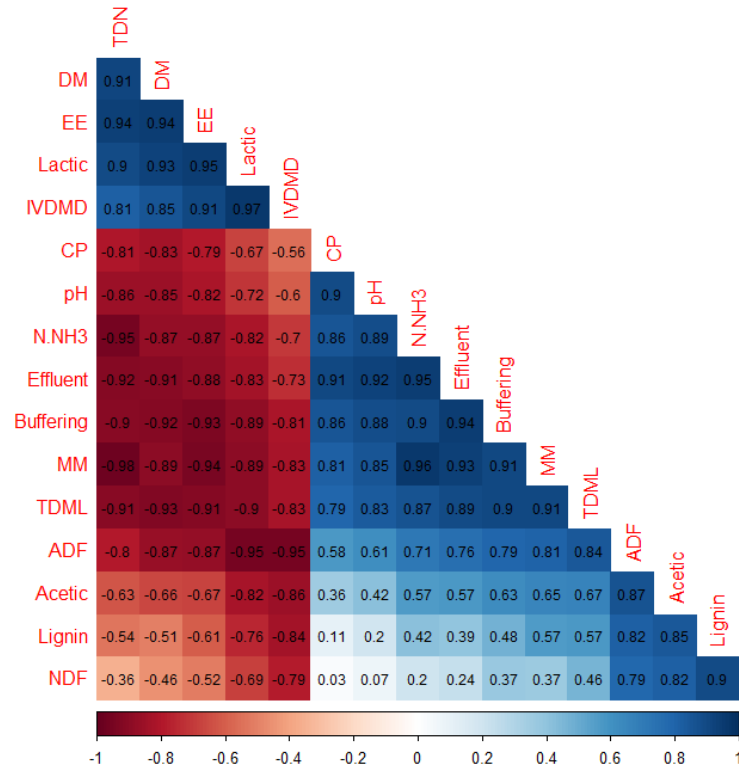


Figure 8. Pearson correlation between fermentation profile variables and nutritive value of silage from maize, Tamani guinea grass, Quenia guinea grass, *Stylosanthes guianensis* cv. Bela and *Stylosanthes* cv. Campo Grande in monocropped and intercropped. Positive correlations are represented by blue backgrounds, and negative correlations by red backgrounds.

TDN: total digestible nutrients; DM: dry matter; EE: ether extract; Lactic: lactic acid; IVDMD: *in vitro* dry matter digestibility; CP: crude protein; pH; N-NH₃: ammoniacal nitrogen; Effluent: effluent production; Buffering: buffering capacity; MM: mineral matter; TDML: total dry matter loss; ADF: acid detergent fiber; Acetic: acetic acid; Lignin: lignin; NDF: neutral detergent fiber.

Through principal component analysis (PCA), it was observed that the first and second components explained 93.5% of the total data variation (Figure 9). The first component, corresponding to the horizontal axis, accounted for 77.8% of the total variation and showed strong correlations with all variables except NDF and Lignin. This component exhibited negative correlations with Lactic, EE, IVDMD, and TDN, and positive correlations with DM, pH, N-NH₃, Buffering, TDML, Effluent, Acetic, MM, CP, and ADF. The second component, corresponding to the vertical axis, explained 15.7% of the data variation and showed a strong negative correlation with NDF and Lignin.

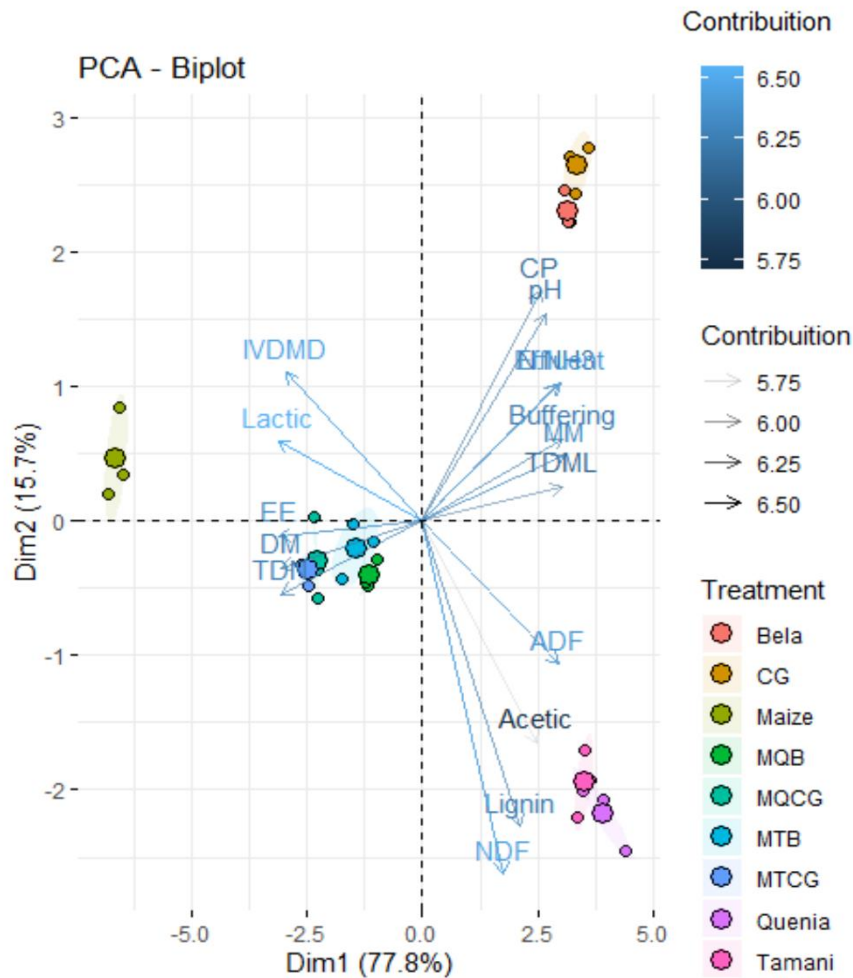


Figure 9. Two-dimensional scatter plot of the principal component analysis (PCA) showing the scores of 16 variables, observations, and treatment means for fermentation profile and nutritive value of silage from maize, Tamani guinea grass, Quenia guinea grass, *Stylosanthes guianensis* cv. Bela and *Stylosanthes* cv. Campo Grande in monocropped and intercropped.

Maize: maize in monocropped; Tamani: Tamani guinea grass in monocropped; Quenia: Quenia guinea grass in monocropped; Bela: *Stylosanthes guianensis* cv. Bela in monocropped ; CG: *Stylosanthes* cv. Campo Grande in monocropped ; MTB: maize intercropped with Tamani guinea grass and Bela; MTCG: maize intercropped with Tamani guinea grass and Campo Grande; MQB: maize intercropped with Quenia guinea grass and Bela; MQCG: maize intercropped with Quenia guinea grass and Campo Grande; TDN: total digestible nutrients; DM: dry matter; EE: ether extract; Lactic: lactic acid; IVDMD: *in vitro* dry matter digestibility; CP: crude protein; pH; N.NH₃: ammoniacal nitrogen; Effluent: effluent production; Buffering: buffering capacity; MM: mineral matter; TDML: total dry matter loss; ADF: acid detergent fiber; Acetic: acetic acid; Lignin: lignin; NDF: neutral detergent fiber.

Through principal component analysis (PCA), it was possible to observe that the variables separated the treatments into four distinct groups: 1: Bela and Campo Grande (CG); 2: Tamani and Quenia; 3: MTB, MTCG, MQB, and MQCG; and 4: maize. Despite the tropical forages (Groups 1 and 2) exhibiting high nutritive value, they present undesirable characteristics that may compromise the fermentation process and preservation of the silage. Thus, the intercropped systems (Group 3) can be used to improve the fermentative characteristics of forage silages in monocropped systems, as well as increase nutritive value, mainly due to the presence of legumes, compared to maize silage in monocropped (Group 4).

4. Discussion

4.1 Dry Matter Production

Integrated systems have demonstrated their potential to synergize environmental regeneration with agricultural production (Zhao et al., 2024). These systems optimize land use efficiency (Farias et al., 2020), ensuring crop diversification and increased food production (Pariz et al., 2018), contributing to global food security (Chowdhuri and Pal, 2025). Additionally, one of the main advantages of integrated systems is the increase in biomass production for ensiling, due to crops growing simultaneously in the same area. This was confirmed in our study, where the highest dry matter production was observed in the triple intercropping of Maize + Tamani guinea grass + Bela and Maize + Quenia guinea grass + Bela.

The *Stylosanthes guianensis* cv. Bela provided greater forage production compared to the *Stylosanthes* cv. Campo Grande. This can be explained by the faster initial growth of Bela (Prado et al., 2024). On the other hand, Campo Grande exhibits slow growth, which is one of the major challenges for the establishment of this legume (Epifanio et al., 2019), and this is further exacerbated in intercropped systems, where the legume faces greater competition, mainly due to shading caused by the more developed maize and Tamani and Quenia guinea grasses.

The impact of pastures on the global economy is significant, especially with the growth of the cattle herd. The choice of fertilization method, whether through soil application or biological nitrogen fixation, is crucial for maintaining soil fertility and forage production (Kokkini et al., 2025). It is important to highlight that in intercropped systems, the incorporation of legumes positively affects forage yield and quality. Additionally, it contributes to reducing the application of mineral nitrogen due to biological nitrogen fixation (Xu et al., 2022). The inclusion of legumes in intercropping schemes and diversified cropping systems can support food security and mitigate environmental risks related to climate change. In this context,

integrated systems have the potential to create a beneficial balance by providing ecosystem services while increasing yields, making triple intercropping a promising strategy for the intensification of high-quality silage production.

4.2 Fermentative Characteristics

The results showed that maize intercropped with grasses and legumes exhibited greater efficiency in the fermentative profile of the silages, characterized by a reduction in pH, a critical indicator of fermentation quality (Peng et al., 2021). In addition, there was an increase in lactic acid production and lower nutrient losses compared to monocropped systems, resulting in more stable silages, with lower effluent production and better dry matter preservation. Silages from monocropped legumes, such as *Stylosanthes guianensis* cv. Bela and *Stylosanthes* cv. Campo Grande, recorded the highest pH values, indicating less efficient fermentation and slower acidification (Lai et al., 2023). Mosebi et al. (2024) attributed this characteristic to the high buffering capacity of legumes, due to the presence of nitrogenous compounds and salts of organic acids, which resist acidification during fermentation, hindering pH reduction (Brito et al., 2020; Hawu et al., 2022). This resistance favours the activity of undesirable microorganisms, such as clostridia and enterobacteria, which degrade proteins and produce nitrogenous compounds, thereby reducing silage quality (Wróbel et al., 2023; Zheng et al., 2024).

Maize silage under monocropped conditions stood out for its lower pH values and buffering capacity, indicating efficient fermentation driven by the predominance of lactic acid bacteria (Guo et al., 2023). This performance is associated with the higher content of soluble carbohydrates in maize, which facilitates rapid and effective acidification, stabilizing the silage and inhibiting the activity of proteolytic microorganisms, thereby contributing to nutrient preservation (Jiang et al., 2020). In intercropped systems, the higher proportion of maize, as shown in Table 1 (average of 70%), promoted a significant reduction in pH compared to monocropped grasses and legumes, favouring more efficient lactic fermentation (Silva et al., 2024b).

The inclusion of maize in intercropping systems proved effective in overcoming these limitations by providing sufficient soluble carbohydrates to offset the typical resistance to acidification observed in legumes, in addition to stimulating greater lactic acid production, which is essential for controlling fermentation and preserving the silage (Gomes et al., 2021). However, legumes alone remain unsuitable for ensiling due to their high buffering capacity and

low water-soluble carbohydrate content, which increase the risk of undesirable fermentations, such as butyric acid production (Hawu et al., 2022; Silva et al., 2023b).

The presence of ammoniacal nitrogen (N-NH₃) is a crucial indicator of silage quality, reflecting the extent of protein degradation that occurs during fermentation (Zhao et al., 2020). N-NH₃ production is generally associated with the breakdown of crude protein promoted by enzymes and microorganisms in the ensiled mass, and the N-NH₃ ratio can reveal the extent of this proteolytic process (Wang et al., 2019). Silages from *Stylosanthes* monocropped, which showed the highest values for these parameters, reflect the challenges of producing silage from sole legumes due to their high buffering capacity and resistance to acidification, characteristics that favour proteolysis and N-NH₃ production (Kung et al., 2018; Mosebi et al., 2024).

Maize silage in a monocropped system, with the lowest values of buffering capacity and N-NH₃, reaffirms its fermentative efficiency due to its ideal carbohydrate profile and lower nitrogen compound content (Jiang et al., 2020). The inclusion of maize in intercropping systems, by providing enough soluble carbohydrates, promoted efficient lactic fermentation, aligning with the findings of Silva et al. (2024b). The results highlight the effectiveness of intercropped systems in improving fermentation, with reductions of 25.03% in buffering capacity and 37.43% in N-NH₃ compared to monocropped systems.

The different silages showed dry matter content within the range of 250 to 350 g kg⁻¹ DM (Figure 4d), considered adequate for the fermentation of the ensiled material (McDonald, 1991). However, Muck and Shinnars (2001) point out that material with dry matter content below 300 g kg⁻¹ may compromise the final silage quality, which affect the fermentation process and increase effluent production. It is important to emphasize that the dry matter content should be considered to determine the cutting time for ensiling, since it influences the compaction of the material and the fermentation process (Teixeira et al., 2021).

The results showed that the cropping systems significantly influenced total dry matter (DM) losses and effluent production (Figure 5). The silages of monocropped *Panicum maximum* and *Stylosanthes* presented the highest DM losses and effluent production, corroborating the findings of Prado et al. (2023), because of their low DM content and high moisture at the time of harvest, factors that favour undesirable fermentations (Wróbel et al., 2023; Marques et al., 2025) and nutrient degradation. In contrast, intercropped systems reduced DM losses by up to 39.99%, especially in silages containing *Stylosanthes* cv. Campo Grande, and decreased effluent production by 29.68%, with emphasis on the intercropping of maize + Tamani guinea grass + Campo Grande. The higher proportion of maize (Table 1) in the silages of the intercropping systems proved to be essential for balancing forage moisture content and

stabilizing fermentation, minimizing losses and preserving nutrients, as pointed out by Paludo et al. (2020).

Maize silage in a monocropped system, with the lowest values of DM losses and effluent production, demonstrates its suitability as a forage for ensiling (Zhang et al., 2022), as it presents good fermentative characteristics (Gomes et al., 2021), such as low pH values and high lactic acid concentration (Kitaw et al., 2024), features that limit the activity of undesirable microorganisms (Kung et al., 2018).

The results for lactic and acetic acid concentrations highlight the effectiveness of including maize in intercropped systems in optimizing the fermentative profile, with a 42.79% increase in lactic acid production and a 9.77% reduction in acetic acid production compared to silage of monocropped tropical forages. This performance is attributed to the higher soluble carbohydrate content of maize, which stimulates the activity of lactic acid bacteria, promoting rapid acidification and nutrient preservation (Souza et al., 2019). In intercropping systems, the interaction between maize and tropical forages may have enhanced the activity of lactic acid co-producing bacteria due to the increase in lactic acid production, compensating for limitations of grasses and legumes and resulting in more efficient fermentation (Meng et al., 2022). The activity of homofermentative lactic acid bacteria, which produce exclusively lactic acid, favours a rapid drop in pH, unlike heterofermentative bacteria, which also produce acetic acid, slowing down acidification (Oliveira et al., 2019; Schmidt and Kung, 2010). The higher acetic acid production observed in tropical forages reflects less efficient fermentation (Tao et al., 2021), while the intercropped systems showed a balance between lactic and acetic acid, indicating proper fermentative control.

4.3 Bromatological Characteristics

The results of the bromatological characteristics of the silages reinforce the relevance of different cropping systems on the final forage quality, with emphasis in the benefits of triple intercropping of maize, cultivars *Panicum* and *Stylosanthes*. The analysis of crude protein (CP) highlighted that the monocropped silages of *Stylosanthes* Campo Grande and Bela presented the highest levels, a fact attributed to the high capacity of legumes to fix atmospheric nitrogen and accumulate proteins (Sharma et al., 2023). This characteristic is widely described in the literature, emphasizing legumes as excellent protein sources due to their distinctive nutritional profile and accumulation of nitrogen compounds (Silva et al., 2022; Marques et al., 2025). However, as previously reported, the ensiling of sole legumes compromises the fermentative

profile and consequently reduces the crude protein content compared to the original ensiled material (Table 2).

On the other hand, silages from intercropping systems proved efficient in increasing CP levels by 26.10% compared to maize silage in monocropped, combining the protein benefits of legumes and grasses with the fermentative and energetic stability of maize. Previous studies support these results, highlighting the potential of double and triple intercropping systems, including legumes, to provide a balanced silage while improving protein content without compromising efficiency (Silva et al., 2024b; Liu et al., 2025).

Regarding fiber fractions such as neutral detergent fiber (NDF), acid detergent fiber (ADF), and lignin, the results showed a clear superiority of maize silage in monocropped, which presented the lowest values for these fractions. This profile is favoured by the lower concentration of structural components and the higher proportion of soluble carbohydrates in maize, characteristics that contribute to greater digestibility and utilization efficiency (Zang et al., 2024). On the other hand, the Tamani guinea grass and Quenia guinea grasses in monocropped presented higher levels of NDF, ADF, and lignin, as described in the literature for tropical grasses (Tesk et al., 2020). These fractions are known to reduce digestibility due to the greater structural complexity of the cell wall (Basso et al., 2024), making degradation by ruminal microorganisms more difficult (Basso et al., 2023). Thus, intercropping systems proved effective in reducing these fiber fractions, with decreases of 14.70% in NDF, 13.76% in ADF, and 44.97% in lignin compared to the monocropped grasses. These results corroborate those observed by Muglia et al. (2025) and reinforce how the intercropping of grains and tropical forages plays a fundamental role in modulating the fibrous characteristics of exclusive forages, facilitating digestibility and nutrient utilization (Bolson et al., 2022).

Maize silage showed higher *in vitro* dry matter digestibility (IVDMD) due to its carbohydrate and lignin content (Ravhuhali et al., 2022), as well as the higher non-fiber carbohydrate content and lower NDF and ADF levels in the silage (Alvarado-Ramírez et al., 2023). However, intercropping systems also showed positive results, with increases of 3.64% and 9.76% in IVDMD compared to cultivars *Stylosanthes* and *Panicum* monocropped, respectively. These data suggest that combining maize with other forages not only improves fermentative stability (Li et al., 2022) but also contributes to greater digestive efficiency, which is essential for animal performance (Rufino et al., 2022). The literature reinforces that intercropping can balance the individual limitations of each forage, providing a more complete and efficient diet for ruminants (Hayat et al., 2024).

Maize silage in monocropped systems showed the highest levels of ether extract and total digestible nutrients (TDN), a fact related to the higher fat content in maize grains, as shown in Table 2. Thus, the higher proportion of maize in the silages of intercropped systems (Table 1) may have contributed to the increase in ether extract and TDN by 29.4% and 15.1%, respectively, compared to tropical forage silages, since tropical forages present low ether extract content. It is important to highlight that ether extract represents the fat content of feeds and as observed in the present study, should show levels like the ensiled material and below 60 g kg^{-1} (Gomes et al., 2021). TDN, on the other hand, represents the energy content of feeds (Marques et al., 2019) and is essential for ruminant production (Daniel et al., 2019).

The correlation and PCA analyses jointly demonstrated the relationships between the fermentative profile and the nutritional quality of the silages (Figures 8 and 9). Showing that silages from integrated systems, such as those in the present study, with the inclusion of cultivars *Panicum* (Tamani and Quenia guinea grasses) and *Stylosanthes* (Bela and Campo Grande), correlate with an increase in dry matter content of tropical forages in monocropped systems, improving lactic acid production and consequently preserving the ensiled material. Furthermore, the silage from the triple intercropping demonstrated no reduction in feed digestibility (Table 1) and, due to the presence of cultivars *Stylosanthes*, improves the nutritional value, especially the crude protein content of the silage compared to maize silage. Thus, these systems may contribute to reducing costs associated with the acquisition of protein salts (Prado et al., 2023), as well as ensuring food security and promoting sustainable diversification of production (Chowdhuri and Pal, 2025).

Additionally, integrated systems contribute to pasture recovery by providing a quality forage during the off-season (Schuster et al., 2019), reducing competition with invasive plants (Mello et al., 2023), producing soil cover biomass for no-till systems (Silva et al., 2023a), increasing nutrient cycling mainly due to the presence of legumes (Fernandes et al., 2025), improving soil health, and contributing to sustainable agriculture (Silva et al., 2025).

It is worth noting that, besides minimizing the issues arising from the fermentative processes of monocropped grasses and legumes silages and improving silage quality, intercropping shows to be an advantageous strategy for producing supplemental roughage. One of its main advantages is providing a pasture area established through intercropping after harvesting the crops for silage (Souza et al., 2019; Oliveira et al., 2020). The development of metrics to evaluate the sustainability of food production systems is vital to achieving sustainable global agrifood systems. Integrated systems allow producers to recover degraded pasture areas at low cost. These findings may support agricultural policies aimed at sustainability, aid

decision-making in agricultural systems, and contribute to practices that maximize productivity while reducing degraded pasture areas in Brazil.

4.4. Conclusion

The results showed that intercropping increased production of dry mass silage and improved fermentation characteristics, reducing by 10.91%; 25.03%; 37.43%; 33.94% and 26.68% in pH, buffering capacity, ammoniacal nitrogen, total dry matter losses, and effluent production, respectively, compared to silages of cultivars *Panicum* and *Stylosanthes* monocropped. In addition, it increased crude protein content in 26.10% compared to maize silage.

Among the *Stylosanthes* cultivars, the Bela cultivar showed the greatest capacity for intercropping. Regarding the *Panicum maximum* cultivars, both can be recommended for intercropping.

It is concluded that a Maize system with *Panicum maximum* and *Stylosanthes* cultivars can be recommended for silage production, focusing on sustainability and reducing costs associated with mineral fertilization.

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4. GENERAL CONCLUSION

Intercropping of crops increases silage mass production by 28.20% and 85.9%, respectively, compared to maize silage and monocropped *Panicum* cultivars and *Stylosanthes*. *Stylosanthes guianensis* cv. Bela presents greater intercropping capacity compared to *Stylosanthes* cv. Campo Grande. Both *Panicum* forages can be recommended for intercropping, as they show similar results.

Intercropped silage improved the fermentative characteristics, reducing pH, buffering capacity, ammoniacal nitrogen, total dry matter losses, and effluent production by 10.91%, 25.03%, 37.43%, 33.94%, and 26.68%, respectively, compared to silages of monocropped *Panicum* cultivars and *Stylosanthes*.

Triple intercropping also provided better nutritional values for the silages, with a 26.10% increase in crude protein content compared to maize silage, balancing the fiber fractions, as well as greater digestibility and total digestible nutrient content compared to monocropped tropical forage silages.

It is concluded that the intercropping of maize with *Panicum* cultivars and *Stylosanthes* can be recommended in integrated silage production systems aiming at sustainability.