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**ANALYSIS OF CONSORTIA, MORPHOMETRIC EVALUATION, CHEMICAL
COMPOSITION OF FORAGE PLANTS AND QUALITY OF MIXED SILAGE FROM
AN INTEGRATED SYSTEM**

TERESINA – PI

2025

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Tese de doutorado apresentada como requisito para aprovação em TESE, do programa de pós-graduação em zootecnia tropical (PPGZT), da Universidade Federal do Piauí, Campus Ministro Petrônio Portella. Como requisito para obtenção do título de doutor em Zootecnia.

Área: Pastagem e Forragicultura

Orientador: Prof. Dr. Ricardo Loiola Edvan

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RESUMO GERAL

O objetivo do Capítulo I foi realizar uma revisão sistemática para analisar os componentes presentes em ecossistemas de consórcios de plantas forrageiras para produção animal. O clima predominante na região, o sistema de consórcio adotado e a escolha das espécies forrageiras são fatores-chave que podem influenciar tanto a biomassa forrageira quanto a de grãos em ecossistemas de consórcios de plantas forrageiras. O objetivo foi analisar os componentes presentes em ecossistemas de consórcios de plantas forrageiras para produção animal no período de 2014 a 2024. A questão de pesquisa foi formulada utilizando a metodologia PICo [População (P), Interesse (I) e Contexto (Co)], com as palavras relacionadas a plantas forrageiras como P, sistema de consórcio como I e sistema de consórcio para produção animal como Co. Operadores booleanos foram utilizados para construir a chave de busca, a saber: População: “plantas forrageiras”, Interesse: “sistemas de consórcio” e Contexto: “sistemas de consórcio para produção animal”. Foram pesquisados artigos nas plataformas Scopus (n = 28), Web of Science (n = 406) e Taylor & Francis (n = 516), totalizando 950 artigos. Desse total, apenas 57 artigos foram selecionados para esta pesquisa. A revisão mostrou que o país com o maior número de pesquisas sobre o tema foi o Brasil, com 23 estudos, seguido pelos Estados Unidos. O consórcio de *Fabaceae* e *Poaceae* representou 61,77% dos estudos, enquanto 19,12% combinaram *Poaceae* e *Poaceae* e 4,41% combinaram *Cactaceae* e *Poaceae*. Foram observados quatorze diferentes domínios climáticos para os sistemas de consórcio analisados, sendo a maioria Aw, seguida por Bsh e Bsk. O consórcio envolvendo milho, *Cactaceae* e sorgo foi o mais produtivo, independentemente do clima predominante na região onde o estudo foi realizado. Pode-se concluir que a biomassa forrageira é variável entre os climas avaliados, e as combinações predominantes de famílias de plantas forrageiras são *Poaceae* - *Fabaceae*, seguidas por *Poaceae* - *Poaceae* e *Poaceae* - *Cactaceae*. O Capítulo II abordou o uso da palma forrageira (*Opuntia ficus indica*), milheto (*Pennisetum glaucum*) e gliricídia (*Gliricidia sepium*), que oferecem benefícios para o consórcio de culturas por terem diferentes exigências de água, nutrientes, floração, frutificação, crescimento vegetativo, arquitetura da copa e distribuição espacial. O objetivo foi avaliar as características morfométricas, a massa de forragem, a composição química, a exportação de proteína bruta e os nutrientes digestíveis totais de plantas forrageiras em sistemas integrados com palma forrageira consorciado com milheto e/ou gliricídia e submetidos a manejo de fertilização orgânica e/ou mineral. Os sistemas integrados foram avaliados utilizando um delineamento inteiramente casualizado, em arranjo fatorial (3x3), com três doses de fertilização: orgânica (AO); mineral (AM); orgânica e mineral (AO+AM); e três sistemas de integração: palma forrageira e milheto (P+M); palma forrageira e gliricídia (P+G); palma forrageira, gliricídia e milheto (P+G+M), cujas médias foram comparadas pelo teste de Tukey com nível de significância de 5%. Houve interação entre os fatores para proteína bruta (PB), fibra em detergente neutro (FDN), fibra em detergente ácido (FDA) e nutrientes digestíveis totais (NDT) da palma forrageira. A palma forrageira acumulou mais PB nos consórcios P+G e P+G+M quando submetido ao manejo com AM ou AO+AM. O milheto foi competitivo e afetou negativamente a composição química da palma no consórcio P+M. As exportações de PB e NDT foram diferentes, com as menores exportações ocorrendo no consórcio P+M. O manejo AO+AM proporcionou maior produção de massa de forragem, exportação de PB e NDT nos sistemas integrados. Este manejo também aumenta a altura, o número de cladódios

e a massa forragem da palma. A produção de massa forragem dos sistemas integrados é a mesma, porém os consórcios P+G e P+G+M exportam mais proteína bruta e nutrientes digestíveis totais do que o consórcio P+M. O Capítulo III avaliou diferentes silagens mistas de sistemas integrados submetidos a manejo de fertilização orgânica e mineral, cultivados com palma forrageira, milho e gliricídia. O objetivo foi avaliar a composição química, microbiológica e os parâmetros de qualidade das silagens mistas da palma forrageira, milho e/ou gliricídia. Toda a massa de forragem produzida, de cada espécie forrageira, na área dos sistemas integrados foi ensilada, a fim de simular a condição real do produtor. Nove tratamentos experimentais foram estabelecidos com quatro repetições, totalizando 36 silos experimentais, cada silo com volume de 3,6 litros. Os silos foram abertos 120 dias após a ensilagem. Adotou-se um delineamento inteiramente casualizado. As médias foram comparadas pelo teste de Scott-Knott com nível de significância de 5%. As silagens avaliadas apresentaram diferenças no teor de matéria seca, que variou de 5,98 a 13,45%. Houve também diferença significativa entre as silagens avaliadas para os parâmetros: pH, carboidratos solúveis e ácidos orgânicos. Não houve diferença para o teor de matéria seca. Não houve diferença para as variáveis nitrogênio amoniacal e estabilidade aeróbica entre as diferentes silagens avaliadas. A estabilidade aeróbica das silagens estudadas durou apenas 3,0 horas após a abertura dos silos. Conclui-se que os sistemas integrados de palma forrageira com gliricídia e adubação orgânica (P+G+AO), adubação mineral (P+G+AM), adubação orgânica e mineral (P+G+AM+AO), bem como os sistemas integrados cultivados com palma, milho e gliricídia com adubação mineral (P+M+G+AM) e adubação mineral/orgânica (P+M+G+AM+AO) produzem forragem que, quando ensilada, apresenta os melhores parâmetros de qualidade dos processos fermentativos, teor de ácidos orgânicos e maior rendimento de matéria seca.

Palavras-chave: ácido acético, ácido butírico, ácido lático, *Cactaceae*, clima, estabilidade aeróbica, *Fabaceae*, *Gliricidia sepium*, *Opuntia ficus indica*, *Pennisetum glaucum*, Perdas por efluentes, *Poaceae*.

GENERAL SUMMARY

The objective of chapter I was to conduct a systematic review to analyze the components present in ecosystems of intercropped forage plants for animal production. The prevailing climate in a region, the intercropping system adopted, and the choice of forage species are key factors that can influence both forage and grain biomass in intercropped forage ecosystems. The objective was to analyze the components present in ecosystems of forage plant consortium for animal production in the period from 2014 to 2024. The research question was formulated using the PICO methodology [Population (P), Interest (I) and Context (Co)], with the words related to forage plants as P, intercropping system as I and intercropping system for animal production as Co. Boolean operators were used to construct the search key, namely: Population: “forage plants”, Interest: “intercropping systems”, and Context: “intercropping systems for animal production”. Articles were searched on the Scopus platform (n = 28), Web of Science (n = 406), and Taylor & Francis (n = 516), totaling 950 articles. Of this total, only 57 articles were selected to be part of this research. The review showed that the country with the most research on the subject was Brazil, with 23 studies, followed by the United States. Intercropping combining *Fabaceae* - *Poaceae* accounted for 61.77% of the studies, while 19.12% combined *Poaceae* - *Poaceae* and 4.41% combined *Cactaceae* - *Poaceae*. Fourteen different climatic domains were observed for the intercropping systems analyzed, most of which were Aw, followed by Bsh and Bsk. Intercropping involving corn, *Cactaceae* and sorghum were the most productive, regardless of the prevailing climate in the region where the study was conducted. It can be concluded that forage biomass is variable between the climates evaluated, and the predominant forage plant families combinations are *Poaceae* - *Fabaceae*, followed by *Poaceae* - *Poaceae*, and *Poaceae* - *Cactaceae*. Chapter II addressed the use of cactus (*Opuntia ficus-indica*), millet (*Pennisetum glaucum*), and gliricidia (*Gliricidia sepium*), which offer benefits for intercropping because they have different requirements for water, nutrients, flowering, fruiting, vegetative growth, canopy architecture, and spatial distribution. The objective was to evaluate the morphometric characteristics, forage mass, chemical composition, crude protein export, and total digestible nutrients of forage plants in integrated systems with cactus intercropped with millet and/or gliricidia and subjected to organic and/or mineral fertilization management. The integrated systems were evaluated using a completely randomized design, in a factorial arrangement (3x3), with three fertilization doses: organic (FO); mineral (FM); organic and mineral (FO+FM); and three integration systems: cactus and millet (C+M); cactus and gliricidia (C+G); cactus, gliricidia, and millet (C+G+M), where the means were compared using Tukey's test with a significance level of 5%. There was an interaction between the factors for crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), and total digestible nutrients (TDN) of the forage palm. The cactus accumulated more CP in the C+G and C+G+M consortia when subjected to management with FM or FO+FM. Millet was competitive and negatively affected the chemical composition of the cactus in the C+M intercropping. CP and TDN exports were different, with the lowest exports occurring in the C+M consortium. FO+FM provides greater forage mass production, CP export, and TDN in the integrated systems. This management also increases the height, number of cladodes, and forage mass of the cactus. The forage mass production of the integrated systems is the same, however the C+G and C+G+M intercropped export more crude protein and total digestible nutrients than the C+M consortium. Chapter III

evaluated different mixed silages from integrated systems subjected to organic and mineral fertilization management, cultivated with forage palm, millet, and gliricidia. The objective was to evaluate the chemical composition, microbiology, and quality parameters of mixed silages of cactus, millet, and/or gliricidia. All the forage mass produced, from each forage species, from the area of the integrated systems was ensiled, in order to simulate the real condition of the producer. Nine experimental treatments were established with four repetitions, totaling 36 experimental silos, each silo with a volume of 3.6 liters. The silos were opened 120 days after ensiling. A completely randomized design was adopted, where the means were compared using the Scott-Knott test with a significance level of 5%. The evaluated silages showed differences for dry matter content, which ranged from 5.98 to 13.45%. There was also a significant difference between the evaluated silages for the parameters: pH, soluble carbohydrates, and organic acids. There was no difference for the variables ammoniacal nitrogen and aerobic stability between the different silages evaluated. The aerobic stability of the studied silages lasted only 3.0 hours after the silos were opened. It is concluded that integrated systems of cactus intercropped with gliricidia with organic fertilization (C+G+FO), mineral fertilization (C+G+FM), organic and mineral fertilization (C+G+FM+FO), as well as integrated systems cultivated with cactus, millet, gliricidia with mineral fertilization (C+M+G+FM) and mineral/organic fertilization (C+M+G+FM+FO) produce forage that, when ensiled, presents the best quality parameters of fermentative processes, organic acid content, and greater dry matter recovery.

Key-words: acetic acid, aerobic stability, butyric acid, *Cactaceae*, climate, effluent losses, *Fabaceae*, *Gliricidia sepium*, lactic acid, *Opuntia ficus-indica*, *Pennisetum glaucum*, *Poaceae*.

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LISTA DE SÍMBOLOS, ABBREVIATURAS E ACRÔNIMOS

°	Celsius degree symbol
°C	Celsius
%	Percentage
®	Trademark
ABS	Aerobic Stability Break
Al	Symbol of the chemical element Aluminum
ADF	Acid Detergent Fiber
Af	Humid equatorial or tropical climate
Aw	Tropical climate, with dry winters
BAL	Lactic Acid Bacteria
BSh	Hot semi-arid climate
BSk	Cold semi-arid climate
Bwh	Hot desert climate, with low precipitation and high evaporation
C ₃	Photosynthetic cycle of plants that ultimately produce 3 carbon molecules
C ₄	Photosynthetic cycle of plants that ultimately produce 4 carbon molecules
C	Carbon
Ca	Symbol of the chemical element Calcium
CAM	Crassulacean acid metabolism
CAPES	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior
CCT	Climate Chamber temperature
CE	Extract saturation indices
Cfa	Humid subtropical climate
Cfb	Humid temperate climate
CFM	Cactus Pear Forage Mass
cm	Centimeters
cm ²	Centimeter Squared
cmol	Centimol
C:N	Carbon Nitrogen Ratio
CO ₂	Carbon dioxide
CP	Crude Protein
CPE	Crude Protein Export
Csa	Temperate (Mediterranean) climate with hot, dry summers
CV (%)	Coefficient of Variation
Cwa	Humid subtropical climate
Cwb	Subtropical highland climate or temperate oceanic climate
Dfb	Humid continental climate with cool summers. It is one of the subtypes of humid continental climate

dm ³	Cubic Decimeter
DM	Dry Mater
DMR	Dry matter recovery
Dsa	Humid continental climate with hot summers and Mediterranean influence
Dwb	Humid continental climate with cool summers and cold, dry winters
EE	Ether Extract
EL	Effluent losses
ENT	Enterobacteria
FAO	Food and Agriculture Organization of the United Nations Brazilian
G	Gram
GEFORPI	Grupo de Extensão de Forragicultura do Piauí
GFM	Gliricidia Forage Mass
g kg ⁻¹	Grams per kilogram
GL	Gas losses
ha	Hectare
IT	Internal silage temperature
K	Symbol for the chemical element Potassium
Kg	Kilograms
kg ha ⁻¹	Kilograms per hectare
K ₂ O	Potassium Chloride
M	Meter
mg	Milligram
m ²	Square meter
m (%)	Aluminum saturation
MFM	Millet Forage Mass
mm	Millimeter
MM	Mineral Matter
MOLD	Molds
N	Nitrogen
NDF	Neutral Detergent Fiber
NM	Natural Matter
NUEFO	Núcleo de Estudos em Forragicultura
O ₂	Oxygen
OF	Organic Fertilizer
OM	Organic Matter
P	Phosphorus
PES	Percentage of exchangeable sodium
(P>0,05)	Probability greater than 5%
(P<0,05)	Probability less than 5%

pH	Hydrogen ion potential
<i>P</i> -valor	Exact probability
P ₂ O ₅	Simple superphosphate
RCI	Relative Chlorophyll Index
S	Sum of bases
SD	Silage density
SEM	Standard Error of the Mean
SPAD	Soil Plant Analysis Development
T	Cation exchange capacity
ton	Tonne
TDN	Total Digestible Nutrient
TDNE	Total Digestible Nutrients Export
TFM	Total Forage Mass
t ha ⁻¹	Tons per hectare
UFPI	Universidade Federal do Piauí
V (%)	Base saturation
YEAST	Yeasts

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CHAPTER I

ANALYSIS OF COMPONENTS PRESENT IN FORAGE PLANT INTERCROPPING ECOSYSTEMS: A SYSTEMATIC REVIEW

ABSTRACT: The prevailing climate of a region, the intercropping system adopted, and the choice of forage species are key factors influencing both forage and grain biomass in intercropped forage ecosystems. This study aimed to analyze the components present in forage plant intercropping systems used for animal production between 2014 and 2024. The research question was developed using the PICo methodology [Population (P), Interest (I), and Context (Co)], with terms related to forage plants defined as the Population, intercropping systems as the Interest, and intercropping systems for animal production as the Context. Boolean operators were used to construct the search strategy, with the following key terms: Population: “forage plants”, Interest: “intercropping systems”, and Context: “intercropping systems for animal production.”. Articles were searched on the Scopus platform (n = 28), Web of Science (n = 406), and Taylor & Francis (n = 516), totaling 950 articles. From this total, only 57 articles were selected to be included in this research. The results showed that Brazil had the highest number of publications on the topic (n = 23), followed by the United States. Intercropping combinations involving Fabaceae - Poaceae were the most frequent (61.77%), followed by Poaceae - Poaceae (19.12%) and Cactaceae - Poaceae (4.41%). Fourteen different climatic classifications were identified among the studies, with Aw being the most common, followed by BSh and BSk. Intercropping systems involving corn, Cactaceae, and sorghum were the most productive, regardless of the prevailing regional climate. Overall, forage biomass varied across the different climatic zones evaluated. The predominant forage family combinations were Poaceae - Fabaceae, followed by Poaceae - Poaceae and Poaceae - Cactaceae.

Key-wors: *Cactaceae*, Climate, Forage biomass, *Fabaceae*, *Poaceae*.

INTRODUCTION

The primary objective of sustainable agriculture is to enhance the productivity of agricultural systems without compromising natural resources for future generations. In this context, forage plant intercropping systems represent an effective strategy for increasing forage biomass, improving soil quality, and reducing the need for chemical inputs (Bell et al., 2014). Intercropping involves cultivating two or more species within the same area. In addition to providing agroecological benefits, such as greater biodiversity and more efficient use of available resources (Moraes et al., 2014), these systems also offer economic advantages by increasing land-use efficiency and

39 enabling the production of multiple outputs, such as forage and grains, within the same
40 area.

41 The inclusion of forage species, particularly those from the *Fabaceae* (legumes)
42 and *Cactaceae* botanical families in combination with *Poaceae* (grasses), enhances
43 the resilience of intercropping systems by improving their ability to withstand adverse
44 weather conditions and biotic stressors, such as pests and diseases (Almeida et al.,
45 2023). Coexisting forage species maximize soil resource use due to their diverse root
46 architectures, which allow nutrient uptake across different soil layers (Sekhon et al.,
47 2018). In *Poaceae* - *Fabaceae* systems, the biological nitrogen fixation performed by
48 *Fabaceae* is essential for enhancing soil fertility (Carvalho et al., 2014; Bybee-Finley
49 et al., 2016; Ligoski et al., 2020).

50 Successful intercropping depends on careful evaluation of several factors,
51 including the forage species involved, the regional climate, the intercropping design,
52 and the specific spatial arrangement of crops. Proper assessment of these
53 components can lead to productive, ecological, and economic benefits, as each factor
54 influences ecological compatibility, nutrient requirements, and growth dynamics within
55 the system. This strategic planning reduces competition for light, water, and nutrients
56 (Moraes et al., 2014). Conversely, when forage species are not ecologically
57 compatible, competition may intensify, often leading to the dominance of one species
58 over another and reducing the system's effectiveness (Pereira et al., 2017). These
59 considerations highlight the need for continued research to better understand the
60 dynamics of integrated production systems (Silva et al., 2018) and to identify
61 agricultural practices that enhance their sustainability (Martins et al., 2023).

62 The interaction between *Poaceae* and *Fabaceae* in intercropping systems
63 deserves particular attention due to the natural compatibility between these botanical
64 families. *Poaceae* species, such as *Megathyrsus maximus*, are valued for their high
65 biomass production and adaptability to a wide range of climatic conditions (Pereira et
66 al., 2014). In contrast, *Fabaceae* species such as gliricidia (*Gliricidia sepium*) are
67 notable for their nitrogen-fixing capacity and their contribution to improved soil fertility
68 (Santos et al., 2018). Species compatibility is one of the most critical determinants of
69 intercropping success, influencing forage yield as well as system persistence and long-
70 term sustainability.

71 Finally, it is important to emphasize that the success of an intercropping system
72 depends not only on the selection of species but also on appropriate pasture

73 management. Given the growing global emphasis on environmental sustainability and
74 the need for more efficient production models, forage intercropping has emerged as a
75 promising approach. Therefore, the objective of this study was to conduct a systematic
76 review to analyze the components present in forage plant intercropping ecosystems
77 used for animal production.

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79 **MATERIALS AND METHODS**

80 The systematic review followed the guidelines of the Preferred Reporting Items
81 for Systematic Reviews and Meta-Analyses (PRISMA), as outlined by Page et al.
82 (2021).

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84 **Search strategy and selection criteria**

85 The literature review was conducted between September and October 2024
86 through electronic searches in the Scopus, Web of Science, and Taylor & Francis
87 databases. Access to these platforms was provided via the CAPES Periodicals Portal,
88 available through the university network of the Federal University of Piauí (UFPI),
89 which ensures open access to these resources. The research question was formulated
90 using the PICo methodology (Population, Interest, and Context). In this framework,
91 terms related to forage plants represented the Population (P), intercropping systems
92 represented the Interest (I), and intercropping systems for animal production
93 represented the Context (Co). Boolean operators were used to build the search string
94 as follows: Population - “forage plants”; Interest - “intercropping systems”; Context -
95 “intercropping systems for animal production.”

96 All search results were screened, exported, and imported into the Mendeley
97 reference management software. The extracted data from the selected studies were
98 then compiled into a Microsoft Excel® spreadsheet for the preparation of figures and
99 graphs.

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101 **Pre-established exclusion criteria**

102 Population: Studies that did not assess forage plants or that included forage
103 plants but not within an intercropping system were excluded. Interest: Studies that did
104 not evaluate forage plants cultivated in intercropping systems were excluded. Context:
105 Studies that did not address intercropping systems involving forage plants for animal

106 production were excluded. Study design: Systematic reviews (with or without meta-
 107 analysis), conference abstracts, books, and book chapters were also excluded.

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109 **Data extraction and analysis**

110 The search identified 28 articles in Scopus, 406 in Web of Science, and 516 in
 111 Taylor & Francis, totaling 950 records (Figure 5). After removing 61 duplicates
 112 appearing in two or more databases, 889 articles remained for title and abstract
 113 screening. Applying the exclusion criteria, 57 peer-reviewed publications were selected
 114 for full analysis. These studies were classified by first author and publication reference,
 115 and the following variables were extracted: regional climate, intercropping type,
 116 intercropped species, location of the intercropping system, forage biomass, and grain
 117 biomass (when reported). Microsoft Excel® was used to compile the dataset and
 118 generate tables, graphs, and maps based on the extracted variables. All 57 selected
 119 articles were included in the reference list.

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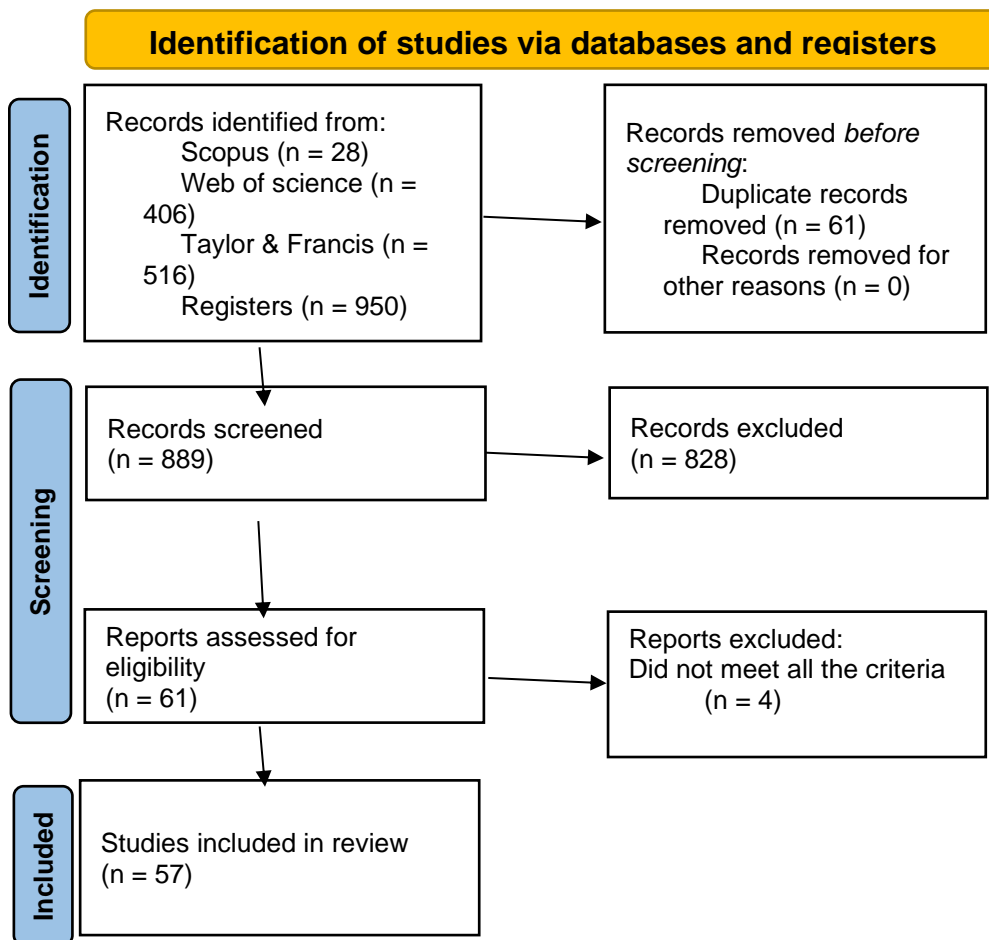


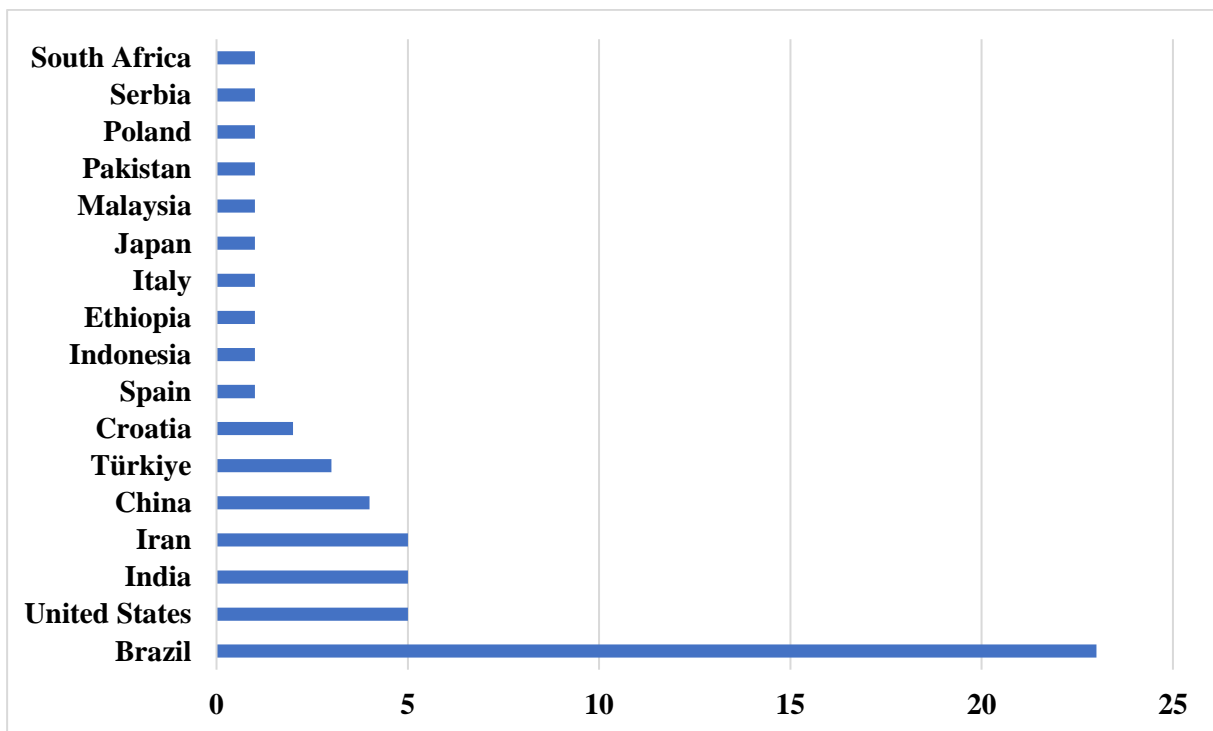
Figure 1. Identification, screening and inclusion of studies via databases and registers

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150 RESULTS

151 Geographic distribution, year of publication of the studies and botanical 152 families used

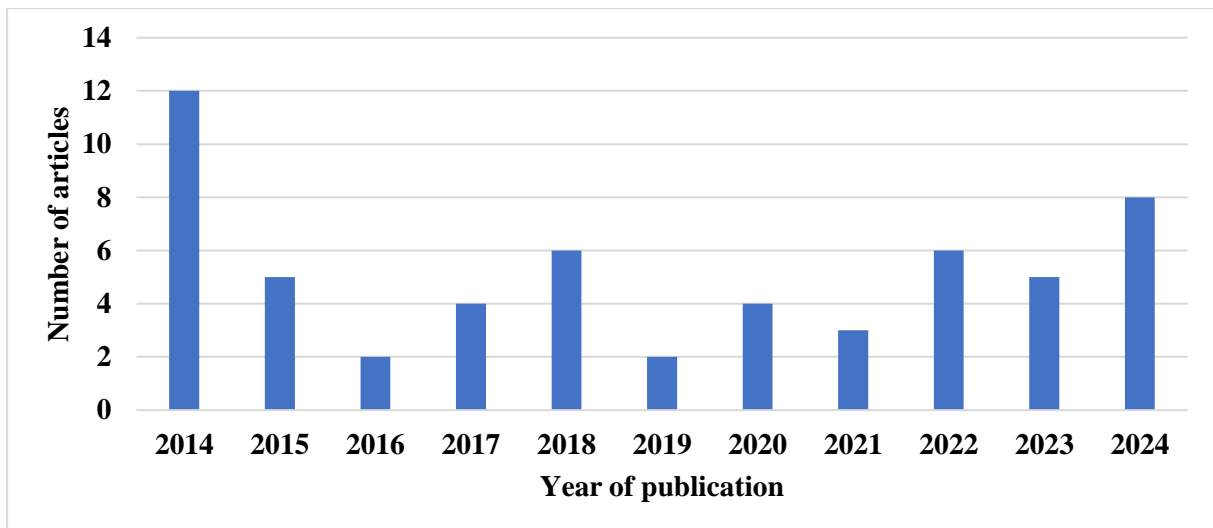
153 Based on the geographical distribution of research on forage plant intercropping
154 systems for animal production, Brazil leads with the highest number of studies (n = 23).
155 It is followed by the United States, China, and Iran, each contributing five studies
156 (Figure 2).



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158 **Figure 2.** Geographical distribution of research evaluating forage plant intercropping systems
159 for animal feeding (Total of 57 articles)

160 Regarding the temporal distribution of the research, most studies were
161 published in 2014, with 12 publications, followed by 2024 with eight publications. In the
162 period from 2014 to 2018, 49.12% of the studies were published, while 50.88% were
163 published between 2019 and 2024 (Figure 3).



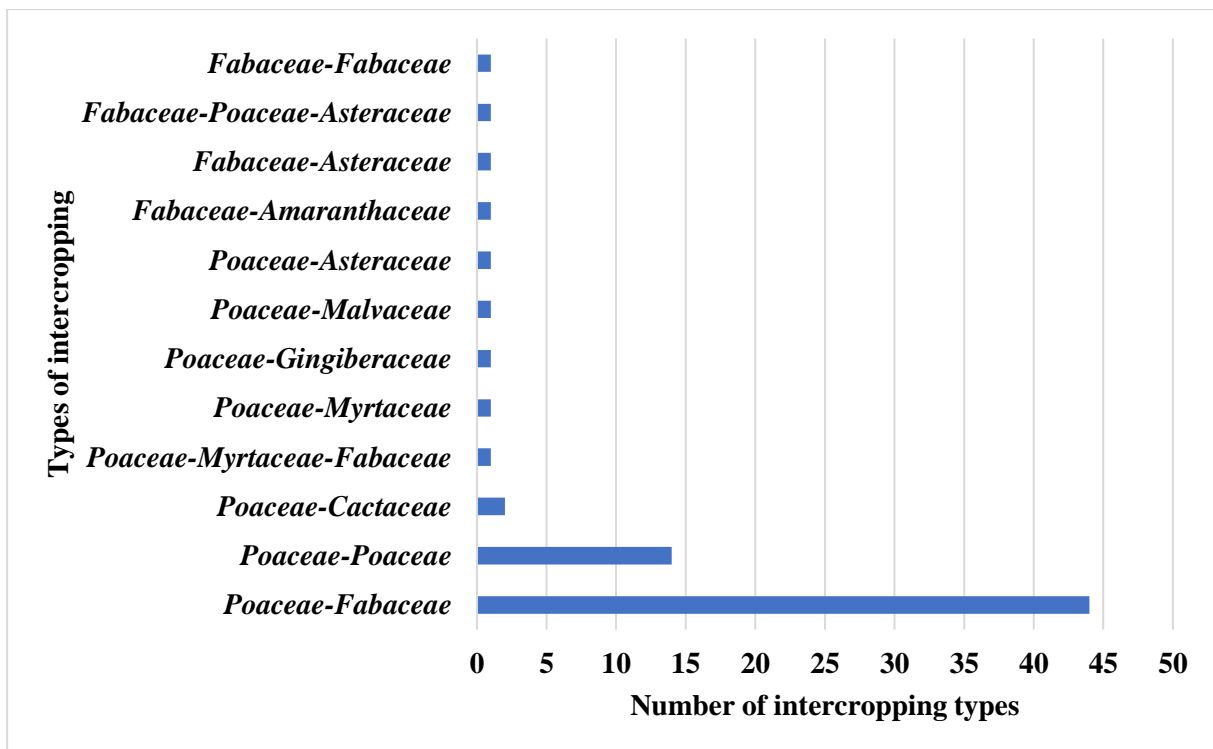
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165 **Figure 3.** Temporal distribution of research evaluating forage plant intercropping systems for
 166 animal feeding

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168 Most studies reported results from intercropping systems combining legumes
 169 and grasses, which accounted for 61.77% of the publications. Intercropping between
 170 *Poaceae - Poaceae* represented 19.12%, while *Cactaceae - Poaceae* combinations
 171 comprised 4.41% of the studies (Figure 4).

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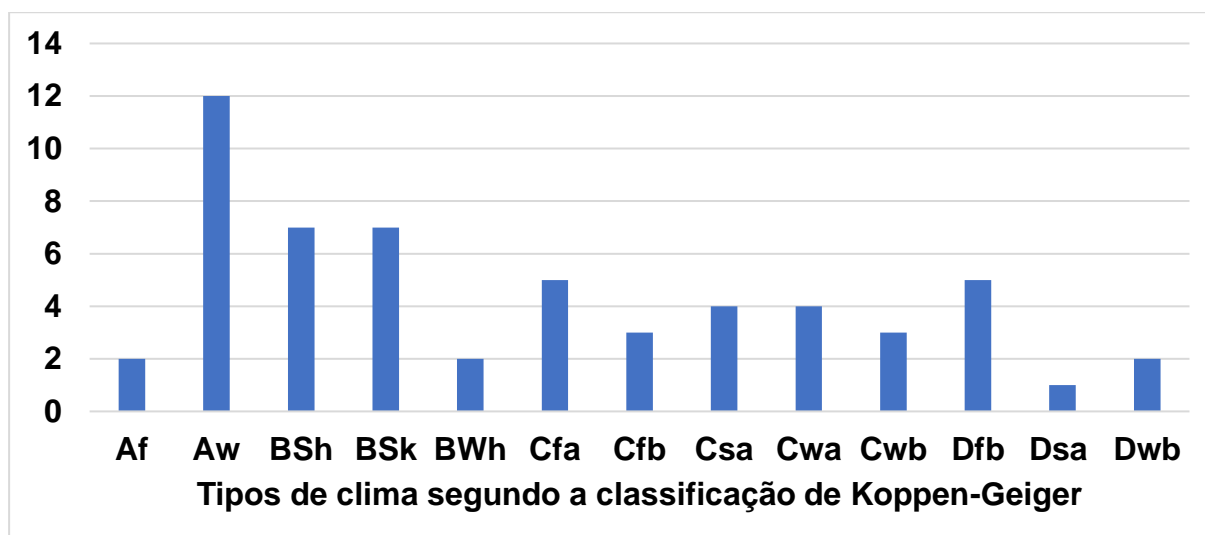


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174 **Figure 4.** Botanical families adopted to compose the different types of forage plant
 175 intercropping used in animal feeding

176 **Forage biomass, forage species used and predominant climate**

177 Research evaluating forage plant intercropping systems for animal feeding
 178 encompassed a wide range of regions, totaling 13 different climatic domains. Most
 179 studies were conducted in areas classified as Aw, characterized by a tropical climate
 180 with distinct rainy and dry seasons (Figure 5).



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 182 **Figure 5.** Climate types according to the Koppen-Geiger classification where the research
 183 evaluating forage plant intercropping systems for animal feeding were conducted

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 185 The highest grain biomass yield was observed in the Cwa climate, averaging
 186 6,737 kg ha⁻¹, followed by the Aw climate with 5,658 kg ha⁻¹. Intercropping systems
 187 involving corn or soybeans demonstrated the highest grain production (Table 1).

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 189 Table 1. Biomass of forage or grains, prevailing climate and forage species used in
 190 intercropping systems to produce animal feed.

Authors	Climate	Intercropped species	Biomass (kg ha ⁻¹)	
			Grains	Forage
(Ernawati et al., 2023)	Af	<i>Indigofera zollingeriana</i> / <i>Pennisetum purpureum</i>		36827
(Baghdadi et al., 2016)	Af	<i>Glycine max</i> / <i>Zea mays</i>		13883
		Mean		25355
		Standard Deviation		16224
(Fernandes et al., 2023)	Aw	<i>Zea mays</i> / <i>Cajanus cajan</i> / <i>Urochloa Brizantha</i>	4785	3726
(Sodré Filho et al., 2021)	Aw	<i>Glycine max L.</i> / <i>Sorghum bicolor</i> / <i>Urochloa brizantha</i> / <i>Urochloa ruziziensis</i>	2922	7948

(Dias et al., 2022)	Aw	<i>Urochloa brizantha</i> / <i>Urochloa ruziziensis</i> / <i>Megathyrus maximum</i> / <i>Glycine max</i> L.		4683
(Oliveira et al., 2020)	Aw	<i>Sorghum bicolor</i> / <i>Urochloa</i> <i>Brizantha</i>	9500	-
(Cruz et al., 2020)	Aw	<i>Sorghum bicolor</i> / <i>Urochloa</i> <i>brizantha</i> / <i>Megathyrus</i> <i>maximum</i> / <i>Phaseolus</i> <i>vulgaris</i>		15004
(Guarnieri et al., 2019)	Aw	<i>Brachiaria brizantha</i> / <i>Zea</i> <i>mays</i>	10112	3418
(Bessa et al., 2018)	Aw	<i>Urochloa brizantha</i> / <i>Phaseolus vulgaris</i> L. / <i>Zea</i> <i>mays</i>		17500
(Domingues et al., 2017)	Aw	<i>Urochloa brizantha</i> / <i>Zea</i> <i>mays</i>		12750
(Gazola et al., 2014)	Aw	<i>Urochloa brizantha</i> , <i>Urochloa ruziziensis</i> / <i>Zea</i> <i>mays</i>	7039	6900
(Saraiva et al., 2014)	Aw	<i>Glycine max</i> / <i>Urochloa</i> <i>brizantha</i>	2450	11293
(Mendonça et al., 2014)	Aw	<i>Urochloa brizantha</i> , <i>Urochloa ruziziensis</i> , <i>Megathyrus maximum</i> / <i>Zea mays</i>		22000
(Sousa et al., 2024)	Aw	<i>Urochloa brizantha</i> / <i>Sorghum bicolor</i>	2800	1830
			Mean	5658
			Standard Deviation	10262
				3246
				6483
(Vieira et al., 2023)	BSh	<i>Cenchrus ciliaris</i> / <i>Moringa</i> <i>oleifera</i>		29400
(Lira et al., 2022)	BSh	<i>Opuntia stricta</i> / <i>Pennisetum glaucum</i>		22000
(Alves et al., 2022a)	BSh	<i>Nopalea cochenillifera</i> / <i>Opuntia stricta</i> / <i>Sorghum</i> <i>bicolor</i>		26563
(Alves et al., 2022b)	BSh	<i>Opuntia stricta</i> / <i>Pennisetum glaucum</i>		27023
(Souza et al., 2017)	BSh	<i>Clitoria ternatea</i> / <i>Cenchrus</i> <i>ciliares</i>		4000
(Zhang et al., 2015)	BSh	<i>Medicago sativa</i> L. / <i>Zea</i> <i>mays</i>		29653

(Ahmad et al., 2015)	BSh	<i>Glycine max, Vigna unguiculata, Phaseolus vulgaris / Zea mays</i>	4309	12550
			Mean	4309
			Standard Deviation	21598
(Umesh et al., 2023)	BSk	<i>Zea mays / Sorghum bicolor L. / Lablab purpureus L. / Phaseolus lunatus L.</i>		19750
(Xu et al., 2022)	BSk	<i>Zea mays / Medicago sativa / Triticum aestivum L.</i>		19700
(Ashoori et al., 2021)	BSk	<i>Trifolium alexandrinum / Sorghum bicolor</i>		22822
(Ghaffarian et al., 2021)	BSk	<i>Kochia scoparia, (Cyamopsis tragonoliba / Sesbania aculeate</i>		5907
(Kahrarian et al., 2021)	BSk	<i>Vicia ervilia / Hordeum vulgare</i>	3280	5440
(Majidi Dizaj et al., 2015)	BSk	<i>Onobrychis vicifolia Scop / Medicago sativa L.</i>		4750
(Sadeghpour et al., 2014)	BSk	<i>Hordeum vulgare L. / Medicago scutellata L.</i>		3481
			Mean	3280
			Standard Deviation	13931
(Lal et al., 2024)	BWh	<i>Pennisetum villosum / Arachis pintoi</i>		2890
(Iqbal et al., 2018)	BWh	<i>Glycine max L. / Sorghum bicolor</i>		5550
			Mean	4220
			Standard Deviation	1882
(Kumar et al., 2021)	Cfa	<i>Lolium multiflorum Lam. / Trifolium alexandrinum</i>		10460
(Mthembu et al., 2018)	Cfa	<i>Lablab purpureus / Zea mays</i>	2277	7979
(Almeida et al., 2017)	Cfa	<i>Megatyrsus maximus / Zea mays</i>	6879	1777
(Bybee-Finley et al., 2016)	Cfa	<i>Pennisetum glaucum / Sorghum bicolor x S. sudanense / Vigna unguiculata / Crotalaria juncea)</i>		9706
(Miyazawa et al., 2014)	Cfa			8730
				7170

		<i>Sorghum bicolor</i> /		6750
		<i>Helianthus annuus</i> L. /		8320
		<i>Crotalaria juncea</i> L.		
			Mean	4578
			Standard Deviation	3254
				7612
				2656
(Abera et al., 2022)	Cfb	<i>Vicia dasycarpa</i> / <i>Vicia villosa</i> / <i>Vicia sativa</i> / <i>Pennisetum glaucifolium</i>		3020
(Jiménez-Calderón et al., 2018)	Cfb	<i>Vicia faba</i> / <i>Brassica napus</i>		19000
(Andrzejewska et al., 2014)	Cfb	<i>Trifolium ambiguum</i> , <i>Triticosecale Wittmack</i> / <i>Secale cereale</i>		9436
			Mean	10485
			Standard Deviation	8042
(Tramacere et al., 2024)	Csa	<i>Hedysarum coronarium</i> L. / <i>Lolium multiflorum</i>		1876
(Aydemir and Kizilsimsek, 2019b)	Csa	<i>Glycine max</i> L. / <i>Sorghum bicolor</i>		2577
(Aydemir, 2019a)	Csa	<i>Glycine max</i> L. / <i>Zea mays</i>		16980
(Serbester et al., 2015)	Csa	<i>Glycine max</i> / <i>Zea mays</i>		10800
			Mean	8058
			Standard Deviation	7197
(Pereira et al., 2014)	Cwa	<i>Urochloa brizantha</i> / <i>Arachis pintoi</i>		20440
(Borghi et al., 2014)	Cwa	<i>Urochloa brizantha</i> / <i>Zea mays</i>	10544	7742
(Crusciol et al., 2014)	Cwa	<i>Glycine max</i> / <i>Urochloa brizantha</i>	2930	9450
(Ceccon and Concenço, 2014)	Cwa	<i>Urochloa ruziziensis</i> , <i>Megatyrus maximus</i> , <i>Urochloa decumbens</i> , <i>Urochloa brizantha</i> / <i>Zea mays</i>		5449
			Mean	6737
			Standard Deviation	5384
				10770
				6652
(Santos et al., 2020)	Cwb	<i>Zea mays</i> / <i>Urochloa brizantha</i> / <i>Brachiaria decumbens</i> / <i>Eucalyptus globulus</i> Labill / <i>Acacia mangium</i>		4288
				4306

(Sahoo et al., 2015)	Cwb	<i>Zea mays</i> / <i>Phaseolus vulgaris</i> / <i>Curcuma longa</i> L. / <i>Hibiscus sabdariffa</i> L.	17750	
			18500	
			16500	
(Wu et al., 2014)	Cwb	<i>Solanum tuberosum</i> L. / <i>Zea mays</i>	8500	
			Mean	11641
			Standard Deviation	6719
(Grabber et al., 2014)	Dfb	<i>Medicago sativa</i> / <i>Zea Mays</i>	17750	
(Uher et al., 2024)	Dfb	<i>Phaseolus vulgaris</i> L. / <i>Sorghum bicolor</i> L.	19760	
(Uher et al., 2019)	Dfb	<i>Zea mays</i> / <i>Phaseolus vulgaris</i> L.	19500	
(Berti et al., 2021)	Dfb	<i>Medicago sativa</i> / <i>Zea Mays</i>	12250	
(Živanov et al., 2018)	Dfb	<i>Vicia faba</i> / <i>Lupinus albus</i> / <i>Triticum aestivum</i> L.	3071	
			3700	
			Mean	3386
			Standard Deviation	445
(Kusvuran et al., 2014)	Dsa	<i>Vicia pannonica</i> Crantz / <i>Hordeum vulgare</i> L.	8030	
			Mean	8030
			Standard Deviation	
(Jiao et al., 2024)	Dwb	<i>Avena sativa</i> L. / <i>Vicia sativa</i>	5220	
(Wei et al., 2024)	Dwb	<i>Medicago ruthenica</i> / <i>Bromus inermis</i>	1961	
			Mean	3591
			Standard Deviation	2304

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192 For forage biomass, the Af climate recorded the greatest yield, reaching 25,355
193 kg ha⁻¹ in intercropping systems involving corn or elephant grass. In the BSh climate,
194 forage biomass was slightly lower at 21,598 kg ha⁻¹, whereas the BSk climate exhibited
195 the lowest yield, with 13,931 kg ha⁻¹. Overall, intercropping systems involving corn,
196 Cactaceae, and sorghum consistently produced the highest biomass, regardless of the
197 prevailing regional climate.

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199 DISCUSSION

200 **Geographic distribution, year of publication of the studies and botanical**

201 **families used**

202 To explain why Brazil leads in the number of studies on intercropping systems
203 (Figure 1), it is essential to consider the country's extensive diversity of forage species,
204 many of which have been introduced or genetically improved. These species form the
205 basis of the diet for Brazil's 238.6 million cattle (IBGE, 2025), which are raised almost
206 entirely on cultivated or natural pastures (Landau et al., 2020). The large volume of
207 studies produced by Brazilian research institutions on sustainability is also influenced
208 by international frameworks such as the United Nations' Agenda 21, which encourages
209 the development of sustainable societies with strong commitments to environmental
210 responsibility (Agenda 21, 2025). This emphasis aligns with the urgent need for
211 agricultural systems that are environmentally balanced and capable of producing low-
212 carbon or carbon-neutral food. Brazil's substantial potential for food production and its
213 strategic role in fostering sustainable agricultural practices and ensuring global food
214 security further reinforce its relevance in this context (Silva et al., 2018; Sodré Filho et
215 al., 2021; Souza et al., 2023). Consequently, in the face of growing global sustainability
216 challenges and rising demand for environmentally responsible farming systems, Brazil
217 has emerged as a key contributor to the development of production models that
218 reconcile productivity with environmental preservation, resulting in a significant
219 increase in scientific publications on this topic (FAO, 2022). Other countries also adopt
220 intercropping systems for animal production, such as Australia, Canada, and New
221 Zealand. However, the participation of these countries was not observed (Figure 1),
222 likely due to the restricted article search methodology used, which considered only the
223 Scopus, Web of Science, and Taylor & Francis databases. The databases commonly
224 used for agricultural science research in these countries include AGRICOLA (NAL
225 Catalog), AGRIS (FAO), CABI (Centre for Agriculture and Bioscience International),
226 PubMed, and Google Scholar (All Databases, 2025).

227 Regarding the temporal distribution of publications, 2024 showed a renewed
228 emphasis on studies involving forage plant intercropping systems (Figure 2), with
229 particular attention directed toward combinations of *Poaceae* and *Fabaceae* species
230 (Figure 3). These studies addressed a range of topics, including biomass production
231 (Javanmard et al., 2020), improvements in forage chemical composition (Abera et al.,
232 2022; Arif et al., 2022), sustainability (Baghdadi et al., 2016; Bell et al., 2014; Carvalho
233 et al., 2014), and reductions in fertilizer use (Santos et al., 2018; Santos et al., 2020).
234 Additional benefits discussed in the literature include enhanced soil fertility, decreased
235 dependence on agrochemicals, and reduced pest pressure (Lira et al., 2021; Pierre et

236 al., 2022), as well as improvements in crop spatial arrangements (Freitas et al., 2021;
237 Almeida et al., 2023). Commonly, these studies evaluate the strategic arrangement of
238 *Poaceae* rows alongside *Fabaceae* species to assess their interactions and the mutual
239 advantages arising from these intercropping configurations.

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241 **Forage biomass, forage species used, and predominant climate**

242 The Cwa climate is classified as humid subtropical, while the Aw climate
243 corresponds to a savannah type with annual rainfall ranging from more than 750 mm
244 up to 1800 mm (Pereira et al., 2017). These climates are characterized by milder
245 temperatures, consistent rainfall, and relatively uniform evapotranspiration during the
246 rainy season. As a result, grain crops experience lower water stress, contributing to
247 greater stability during their growth and development (Borghi et al., 2014). In these
248 regions, intercropping systems involving corn and soybean are the most common
249 (Ceccon and Concenço, 2014). The Af climate, also known as a humid or super-humid
250 tropical climate, or equatorial rainforest climate, offers highly favorable conditions for
251 forage biomass production. These include temperatures above 15°C, abundant solar
252 radiation with approximately 12 hours of daylight throughout the year, minimal
253 photoperiod variation, consistent rainfall, and fertile soils (Baghdadi et al., 2016). Under
254 such conditions, intercropping systems typically include highly productive C4 grasses
255 with high photosynthetic efficiency, such as *Pennisetum purpureum* (Ernawati et al.,
256 2023) and *Zea mays* (Mthembu et al., 2018). These grasses are often combined with
257 C3 legumes, such as *Indigofera zollingeriana* and *Glycine max*, which enhance soil
258 fertility and contribute to the nutritional balance within the system (Baghdadi et al.,
259 2016).

260 In semi-arid regions, where the predominant climate is classified as BSh,
261 intercropping systems involving cacti and grasses have received increasing attention
262 due to their resilience under drought conditions. Species of *Opuntia* and *Nopalea*,
263 which utilize CAM metabolism, offer a substantial advantage by efficiently storing water
264 and energy, resources that are essential during prolonged dry periods (Alves et al.,
265 2022). When intercropped with *Poaceae* or *Fabaceae*, cacti contribute to highly
266 productive systems, with forage yields reaching 21,598 kg ha⁻¹ of high-quality biomass
267 (Table 1S). Studies further indicate that *Cactaceae* - *Poaceae* intercropping improves
268 the efficiency of soil and water use, particularly in areas affected by soil degradation
269 (Souza et al., 2023).

270 The intercropping of *Cactaceae* and *Fabaceae* species represents a promising
271 strategy for regions with limited water availability, such as those characterized by a
272 BSh climate. This system combines the drought tolerance of cacti with the nitrogen-
273 fixing capacity of legumes, thereby enhancing soil fertility and overall resource-use
274 efficiency (Souza et al., 2023). As a result, it supports a low-input production model
275 and provides a valuable source of water, energy, and protein for animal feeding
276 (Santos et al., 2018; Vieira et al., 2023).

277 The intercropping of forage plants is a valuable strategy in pasture-based
278 systems, aiming to improve both the nutritional quality of animal feed and grain
279 production. Grasses such as *Urochloa brizantha* (brachiaria grass) and *Megathyrsus*
280 *maximus* (mombaça grass) are recognized for their high productivity and palatability
281 and can be efficiently intercropped with corn (*Zea mays*) (Ceccon and Concenço,
282 2014). These *Poaceae* - *Poaceae* intercropping systems contribute to the development
283 of more productive and resilient pastures capable of meeting diverse demands for
284 forage and grain production (Pereira et al., 2014; Silva et al., 2014). A key advantage
285 of such combinations is the substantial increase in vegetative ground cover, which
286 plays a critical role in preventing soil erosion, enhancing soil fertility, improving nutrient
287 availability, and maintaining soil moisture (Santos et al., 2020). Furthermore, *Poaceae*
288 - *Poaceae* intercropping promotes system sustainability by reducing vulnerability to
289 specific pests and diseases and ensuring more consistent pasture availability
290 throughout the year (Moraine et al., 2014).

291 *Fabaceae* species such as alfalfa (*Medicago sativa*) stand out for their excellent
292 chemical composition and high forage productivity. These attributes have made alfalfa
293 a frequent subject of scientific investigations across a wide range of climates and
294 geographic regions (Berti et al., 2021). In addition to alfalfa, other legume crops such
295 as *Crotalaria juncea* (crotalaria) also play important roles in intercropping systems
296 (Bybee-Finley et al., 2016; Silva et al., 2018).

297 A notable example of a successful *Poaceae* - *Fabaceae* intercropping system
298 is the combination of star grass (*Cynodon* spp.) with peanut (*Arachis pinto*), which
299 contributes significantly to the development of more sustainable pasture systems (Lal
300 et al., 2024). In this arrangement, the grass functions as the primary forage source for
301 livestock, while the legume enhances soil quality by contributing organic matter and
302 supplying nitrogen through biological fixation (Pereira et al., 2017). Owing to its
303 prostrate growth habit, peanut often evades grazing pressure, enabling it to persist in

304 the system and maintain its role in soil fertility improvement. This type of intercropping
305 is particularly beneficial in rotational grazing systems, where the rapid regrowth
306 capacity of *Poaceae* is essential to ensuring a consistent and reliable forage supply
307 (Carvalho et al., 2014).

308

309 **CONCLUSION**

310 Forage biomass varies across the climatic conditions evaluated, with the most
311 common intercropping systems involving grass - legume combinations, followed by
312 grass - grass and grass - cactus systems. However, a substantial gap remains
313 regarding studies that include other botanical families. Thus, further research is
314 needed to explore and assess intercropping systems incorporating a broader diversity
315 of forage plant families.

316 Corn and soybean stand out as the most commonly used species for forage and
317 grain production in intercropping systems across the different climates evaluated.

318 The combination of different botanical families provides distinct advantages,
319 including enhanced soil fertility and greater resilience to adverse environmental
320 conditions, such as drought. These intercropping models enable more sustainable
321 livestock production by reducing dependence on external inputs and increasing the
322 year-round availability of forage or grain biomass. Consequently, such systems
323 contribute directly to food security and to the long-term sustainability of agricultural
324 activities in regions with challenging climatic conditions.

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CHAPTER II

MORPHOMETRY, CHEMICAL COMPOSITION AND NUTRIENT EXPORT OF FORAGE PLANTS IN INTEGRATED SYSTEMS

Abstract: The combination of cactus pear (*Opuntia ficus-indica*), millet (*Pennisetum glaucum*), and gliricidia (*Gliricidia sepium*) offers advantages for intercropping, as these species differ in their water and nutrient needs, flowering and fruiting periods, vegetative growth patterns, canopy structures, and spatial arrangements. This study aimed to evaluate the morphometric characteristics, forage mass, chemical composition, crude protein export, and total digestible nutrients in integrated systems of cactus pear intercropped with millet and/or gliricidia and subjected to organic and/or mineral fertilization. A completely randomized design was adopted in a factorial arrangement (3 × 3), with three fertilizer rates: organic (OF), mineral (MF), organic and mineral (OF+MF); and three integration systems: cactus pear and millet (C+M), cactus pear and gliricidia (C+G), cactus pear, gliricidia, and millet (C+G+M). The means were compared through the Tukey's test with a significance level of 5%. There was a significant effect of interaction ($P < 0.01$) between the factors on crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), and total digestible nutrients (TDN) of cactus pear, which accumulated more CP in the C+G and C+G+M combinations when subjected to management with MF or OF+MF. Millet was competitive and negatively affected the chemical composition of cactus pear in the C+M intercropping. CP and TDN exports were different ($P < 0.05$), with the lowest exports occurring in the C+M intercrop. OF+MF provides greater forage mass yield, CP and TDN exports from the integrated systems. This management also increases the height, number of cladodes, and forage mass of cactus pear. The forage mass production of the integrated systems is the same, but the C+G and C+G+M combinations export more crude protein and total digestible nutrients than the C+M intercropping.

Keywords: mineral fertilization, organic fertilization, gliricidia, millet, cactus pear

INTRODUCTION

Integrated forage production systems are more efficient ways to use land, aiming to maintain sustainability and produce more than one plant species in the same area, while also offering diverse feed for the animals (Saraiva et al., 2022; Herrera Angulo et al., 2023). Therefore, understanding the agronomic characteristics of forage plants, managing mineral and organic fertilizers, and diversifying the use of plant species within integrated systems are important strategies for maximizing productivity. Furthermore, ruminant animals have energy, protein, and mineral requirements that are only met when combining more than one forage species (Gomes et al., 2023).

725 In the dry regions of Brazil, where rainfall is both scarce and irregular, it is
726 essential to cultivate adapted, productive, and drought-tolerant species capable of
727 withstanding the long dry seasons that often last up to eight months each year. (Dos
728 Santos et al., 2023). The cactus pear (*Opuntia ficus indica*), millet (*Pennisetum*
729 *glaucum*), and gliricidia (*Gliricidia sepium*), which have already been shown to be
730 adapted to the Brazilian tropical climate, present benefits for intercropping, as they are
731 a *Cactaceae*, a *Poaceae* and a *Fabaceae*, which have different requirements for water,
732 nutrients, flowering, fruiting, vegetative growth, canopy architecture and spatial
733 distribution, being indicated for intercropping in the integrated system (Souza et al.,
734 2022; Souza et al., 2023; Saraiva et al., 2022; Herrera Angle et al., 2023).

735 Mineral fertilization based on fertility analysis allows for the supplementary
736 supply of deficient nutrients in the soil to meet the nutritional requirements of forage
737 plants and achieve productivity objectives for each crop (Liu et al., 2023). The use of
738 organic fertilization is also advantageous because it increases the availability of
739 nutrients in the soil, such as nitrogen, phosphorus, and potassium. It adds organic
740 matter to the soil, enriching it with a greater diversity of nutrients and microorganisms,
741 while enhancing soil texture, water retention, moisture, and aeration (Saraiva et al.,
742 2022; Herrera Angle et al., 2023).

743 Our hypothesis is that the intercropping of cactus pear with gliricidia and millet,
744 combined with mineral, organic, and mineral fertilizers, increases forage mass, protein
745 export, total digestible nutrients, and improves forage chemical composition in the
746 integrated system. In this context, the objective of this research was to evaluate the
747 morphometric characteristics, forage mass, chemical composition, crude protein
748 export, and total digestible nutrients of cactus pear intercropped with millet and/or
749 gliricidia, and subjected to organic and/or mineral fertilizer management.

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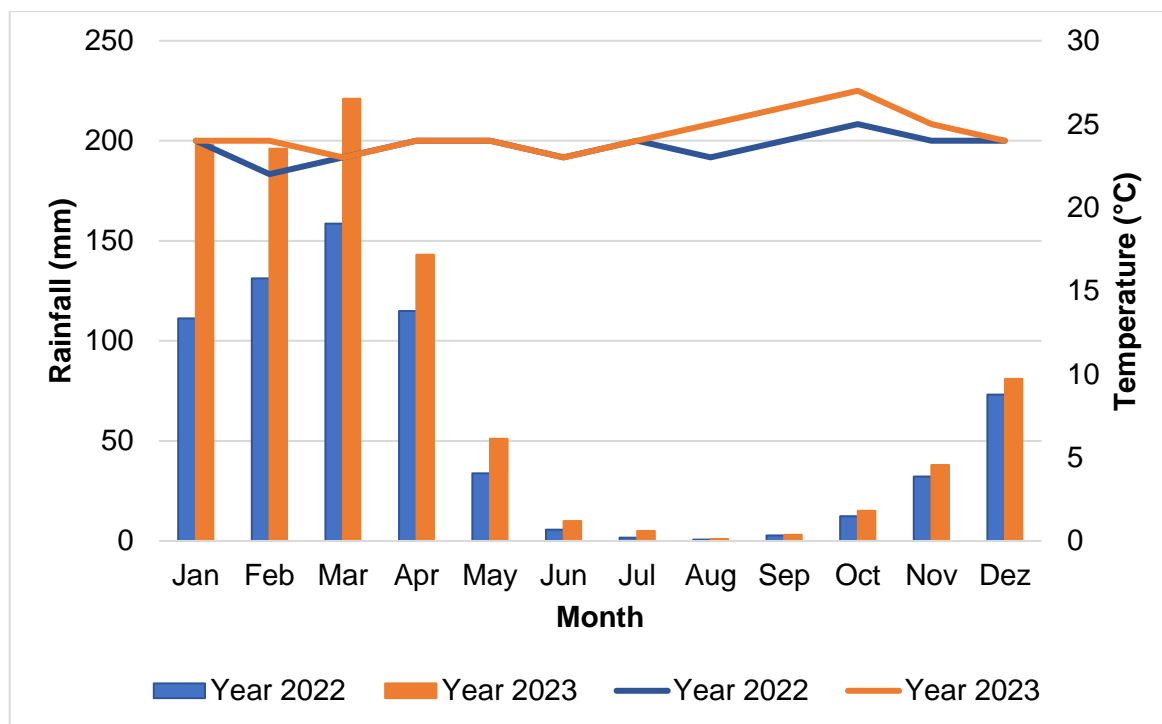
751 **MATERIALS AND METHODS**

752 **Location and establishment of integrated systems**

753 The experiment was conducted at the Federal Institute of Education, Science
754 and Technology of Piauí - IFPI, in the town Valença do Piauí, Piauí, Brazil, located
755 at geographic coordinates 6°25'23.5" S and 41°45'02.9" W. The climate of the
756 region is classified as Aw, hot and tropical, according to the Köppen climate
757 classification (Köppen,1936), with minimum temperatures of 22 °C and maximum
758 of 37 °C. The average annual rainfall is 1,103 mm, ranging from 800 to 1,400 mm,

759 with about 5 to 6 months as the rainiest and the remaining period of the year as the
 760 dry season (Medeiros *et al.*, 2020). Rainfall and average temperature during the
 761 experimental period are shown in Figure 6.

762



763

764 **Figure 6.** Rainfall and average temperature in Valença do Piauí in 2022 and 2023

765

766 Nine integrated systems were established in 36 plots with 12 m² of useful
 767 area (6m×2m), using different combinations between the species (Figure 7): cactus
 768 pear (*Opuntia ficus indica*), millet (*Pennisetum glaucum*), and gliricidia (*Gliricidia*
 769 *sepium*), with each integrated system associated with a different organic and
 770 mineral fertilization management.

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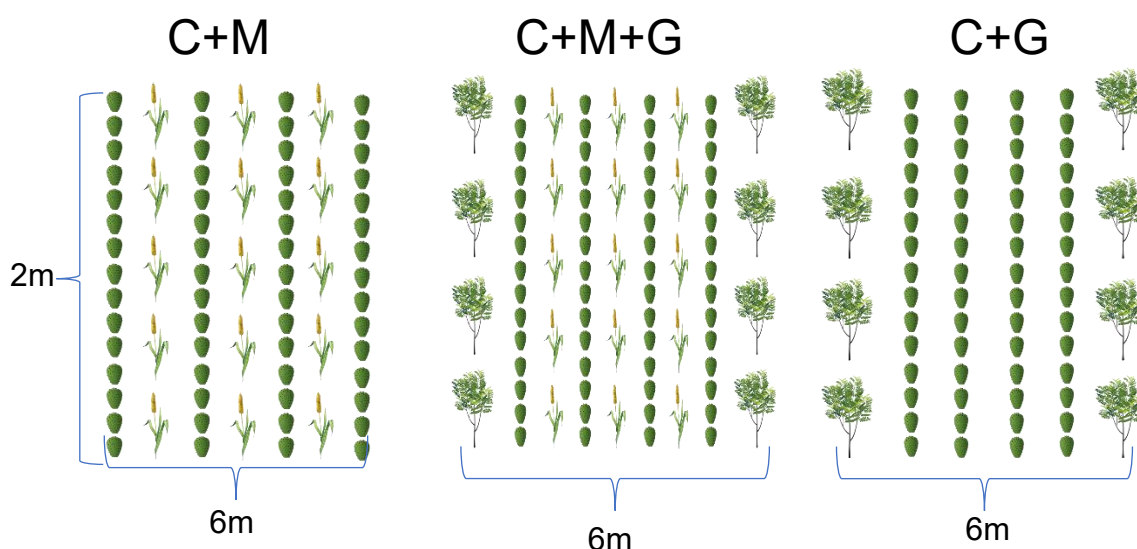
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782 **Figure 7.** Integrated systems with cactus and millet (C+M), cactus, gliricidia and millet
 783 (C+G+M), cactus and gliricidia (C+G)

784

785 The factors analyzed consisted of three integration systems: cactus pear and
 786 millet (C+M); cactus pear and gliricidia (C+G); cactus pear, gliricidia, and millet
 787 (C+G+M); and three fertilizers: organic (OF); mineral (MF); organic and mineral
 788 (OF+MF), with four replicates. After soil analysis, liming was performed to increase
 789 base saturation to 70% and pH 6.0 (Martha Júnior et al., 2007) (Table 1).

790

791 **Table 1.** Soil analysis at a depth of 0-20 cm, and composition of the organic fertilizer.

Soil analysis									
Soil granulometric composition (g/kg)						-----			
Coarse sand	Fine sand	Clay	Silt	Natural clay	CE	pH			
59	633	149	159	65	dS /m	water			
Soil Sorption Complex (cmol _c /kg)						0.11	5.2		
Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	H ⁺ +Al ³⁺	Al ³⁺	S	T		
0.20	0.5	0.08	0.12	4.45	1.25	0.9	5.4		
C (g/kg)	N	C/N	OM	P (mg/kg)	V (%)	m (%)	PES		
792	0.85	9.0	13.65	2	58	17	2		
Analysis of the composition of organic fertilizer (OF)									
N	C	C/N	P	K	Ca	Mg	S	Na	
g/kg	g/kg	-	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg	
9.7	115.4	12.0	2.7	9.1	21.1	5.5	2.0	0.8	

792 CE: extract saturation indices; S: sum of bases; T: cation exchange capacity; V (%): base saturation;
 793 m (%): aluminum saturation; PES: percentage of exchangeable sodium.

794

795 The area was harrowed, and three fertilization treatments were applied:
796 organic fertilizer (OF), mineral fertilizer (MF), and a combination of mineral and
797 organic fertilizer (MF + OF). The OF treatment consisted of a single application of
798 35,000 kg ha⁻¹ year⁻¹, using a 1:1 mixture (dry weight basis) of cattle manure and
799 poultry litter. The MF treatment involved the application of 100 kg ha⁻¹ P₂O₅ (70 kg
800 at planting and 30 kg as a topdressing, from single superphosphate), 70 kg ha⁻¹
801 K₂O (from potassium chloride), and 200 kg ha⁻¹ N as a topdressing, split into three
802 applications (from urea). The MF + OF treatment combined both mineral and
803 organic fertilization strategies. The nutrient composition of the organic fertilizer is
804 shown in Table 1.

805 Gliricidia was planted with 20 cm cuttings at a spacing of 6 m × 0.5 m,
806 corresponding to 3,125 plants per hectare. Cactus pear was planted between the
807 gliricidia rows using mother cladodes buried 50% in the soil, with a spacing of 1.5
808 m × 0.2 m, corresponding to 33,330 plants per hectare. Millet was sown in a
809 continuous line between the cactus rows (0.7 m between rows).

810

811 **Morphometry and chemical composition of forage species**

812 The height of cactus pear, millet, and gliricidia was measured with a tape
813 measure, positioned from the ground to the highest point of each forage plant. Height
814 measurements were obtained in three plants per plot. Subsequently, the chlorophyll
815 relative index (CRI) was measured for these plants with a SPAD 502® chlorophyll
816 meter (Godoy et al., 2008). The average number of cladodes was obtained from two
817 cactus pear plants per plot. Plant density in millet was obtained by counting the number
818 of plants per 1.8 linear meters in each experimental plot. Cactus pear and millet were
819 evaluated at 720 and 70 days after planting, respectively. Gliricidia was evaluated at
820 70 days of regrowth. All species were evaluated on the same day, at harvest.

821 Samples of forage species from the integrated systems were collected,
822 identified, and sent to the Animal Nutrition Research Laboratory (LAPEN) of the
823 Federal University of Piauí (UFPI) for analysis of the chemical composition of the
824 forage. The dry matter (DM) content was determined at 105°C, and crude protein (CP,
825 method 988.05), and mineral matter (MM, method 942.05) were determined according
826 to the AOAC (2012) procedures. The neutral detergent fiber (NDF) and acid detergent
827 fiber (ADF) fractions were obtained from the methodology described by Mertens et al.
828 (2002), adapted for autoclave equipment (105°C/60 min) according to Barbosa et al.

829 (2015), who used 4 × 5 cm non-woven fabric bags (TNT, 100 g/m²), with porosity of
830 100 µm. The ether extract (EE) was determined through extraction process with
831 solvents, such as ether, in a Soxhlet-type apparatus, using the Randall method
832 (Method G-005/2). The total digestible nutrients (TDN) were estimated as described
833 by Cappelle et al. (2001) for roughage feeds by the equation:

$$834 \quad \text{TDN(\%)} = 91.6086 - 0.669233 \times (\text{NDF}) + 0.437932 \times (\text{CP})$$

835 **Forage mass, protein export and total digestible nutrients**

836 Millet forage mass was determined by cutting the plants at ground level, within
837 1.8 linear meters, obtaining the fresh weight and converting it to kg ha⁻¹. All cactus pear
838 plants in the experimental plot were cut, preserving the primary cladodes, and
839 weighed. To obtain the gliricidia forage mass, three plants per plot were cut at a height
840 of 50 cm from the ground. After obtaining the forage masses of cactus pear (CFM),
841 millet (MFM), and gliricidia (GFM), the total forage mass (TFM) was determined, in kg
842 ha⁻¹ of DM, according to the equation below:

$$843 \quad \text{TFM} = \text{CFM} + \text{MFM} + \text{GFM}$$

844 Where: CFM = cactus pear forage mass; MFM = millet forage mass; GFM = gliricidia
845 forage mass.

846 Then, the export of crude protein (CPE) in kg ha⁻¹ of CP was determined,
847 according to the equation:

$$848 \quad \text{CPE} = (\% \text{CPc} \times \text{CFM}) + (\% \text{CPm} \times \text{MFM}) + (\% \text{CPg} \times \text{GFM})$$

849 Where: %CPc, %CPm and %CPg are the crude protein contents of cactus pear, millet
850 and gliricidia, respectively.

851 Total digestible nutrient export (TDNE) in kg ha⁻¹ of TDNE, according to the
852 following equation:

$$853 \quad \text{TDNE} = (\% \text{TDNc} \times \text{CFM}) + (\% \text{TDNm} \times \text{MFM}) + (\% \text{TDNg} \times \text{GFM})$$

854 Where: %TDNc, %TDNm and %TDNg are the total digestible nutrient contents of
855 cactus pear, millet and gliricidia, respectively.

856

857 **Statistical analysis**

858 The data were analyzed using analysis of variance (ANOVA), with normality
859 assessed by the Shapiro-Wilk test and homogeneity of variances verified using
860 Bartlett's test. Data on chemical composition, morphometry, forage mass, protein
861 export and total digestible nutrient export were analyzed using a completely

862 randomized design, in a factorial arrangement with three fertilization managements
 863 and three crop combinations (3 × 3) in four replications, according to the following
 864 mathematical model adopted:

$$y_{ij} = \mu + t_i + b_j + (t \times b)_{ij} + e_{ij}$$

865
 866 where: y_{ij} = observed value in the plot of the i^{th} factor 1 in the j^{th} factor 2; μ =
 867 experimental mean; t_i = effect of the i^{th} factor 1 in the experimental plot; b_j = effect of
 868 the j^{th} factor 2 in the experimental plot; $(t \times b)_{ij}$ = effect of interaction between factor 1
 869 and factor 2; e_{ij} = uncontrolled random error in the plot of the i^{th} factor 1 in the j^{th} factor
 870 2. Tukey's test was adopted with a significance level of 5% ($P \leq 0.05$). The analyses
 871 were performed using the SISVAR software (Ferreira, 2011).

872

873 RESULTS

874 Fertilizer management significantly affected the height of cactus pear, gliricidia,
 875 and millet ($P < 0.01$ for all species), with the greatest values observed under the OF+MF
 876 treatment compared to MF alone. In cactus pear, the OF+MF treatment also resulted
 877 in a higher number of cladodes, averaging 15.8 cladodes per plant (Table 2).

878

879 **Table 2.** Morphometric characteristics and chlorophyll index in forage species
 880 cultivated in integrated systems subjected to different fertilization management.

Intercropping (I) ¹	Fertilization (F) ²			Mean	<i>p</i> - value F	<i>p</i> - value I	<i>p</i> - value I×F
	MF	OF	OF+MF				
Cactus pear height (cm)					< 0.01	0.48	0.45
C+M	74.2	65.2	87.6	75.7 ^A			
C+G	77.7	74.4	81.3	77.8 ^A			
C+G+M	83.1	72.5	85.0	80.2 ^A			
Mean	78.3 ^{ab}	70.7 ^b	84.6 ^a				
Number of cladodes of the cactus pear (n plant ⁻¹)					< 0.01	0.97	0.16
C+M	10.5	7.1	18.4	12.0 ^A			
C+G	10.8	11.5	14.0	12.1 ^A			
C+G+M	12.0	8.5	14.9	11.8 ^A			
Mean	11.1 ^b	9.0 ^b	15.8 ^a				
Gliricidia height (cm)					< 0.01	0.17	0.74
C+G	119.5	139.1	168.4	142.2 ^A			
C+G+M	125.1	165.7	183.7	158.1 ^A			
Mean	122.3 ^b	152.4 ^{ab}	176.0 ^a				
RCI of gliricidia (SPAD unit)					0.96	0.84	0.96
C+G	36.7	36.0	37.4	36.7 ^A			
C+G+M	36.7	34.8	38.2	36.5 ^A			

Mean	36.7 ^a	35.4 ^a	37.8 ^a			
	Millet height (cm)				< 0.01	0.76 0.22
C+M	61.4	76.6	72.6	70.2 ^A		
C+G+M	56.3	68.1	82.7	68.8 ^A		
Mean	58.8 ^b	72.3 ^{ab}	77.4 ^a			
	RCI of millet (SPAD unit)				0.34	0.67 0.07
C+M	46.5	46.9	43.1	45.5 ^A		
C+G+M	47.8	39.4	53.1	46.8 ^A		
Mean	47.1 ^a	43.1 ^a	48.1 ^a			
	Plant density (plant m ⁻¹)				0.04	0.82 0.48
C+M	140.3	214.4	171.0	174.6 ^A		
C+G+M	152.5	183.0	179.6	172.3 ^A		
Mean	146.4 ^b	198.7 ^a	175.3 ^{ab}			

881 ¹cactus pear and millet (C+M); cactus pear and gliricidia (C+G); cactus pear, gliricidia and millet
882 (C+G+M). ²Organic fertilization (OF); mineral fertilization (MF); organic and mineral fertilization
883 (OF+MF). Lowercase and uppercase letters compare means in the row and column, respectively, at the
884 5% significance level according to the Tukey's test.

885

886 The RCI of gliricidia and millet was not affected by the evaluated factors.
887 However, millet plant population density varied significantly among fertilization
888 treatments ($P = 0.04$), with 146.4 plants per linear meter under the MF treatment, 198.7
889 under OF, and 175.3 under OF+MF.

890 A significant interaction ($P < 0.01$) was observed between the factors for CP,
891 NDF, ADF, and TDN in cactus pear. In the integrated C+M system, millet reduced CP
892 accumulation in cactus pear, with 6.1% under OF+MF, compared to 8.2% in C+G.
893 Cactus pear also showed higher CP accumulation in the C+G and C+G+M
894 combinations when managed with MF or OF+MF (Table 3).

895

896 **Table 3.** Factors and interaction outcomes for the chemical composition of cactus pear
897 in the integrated system subjected to different fertilization management

Intercroppin g (l) ¹	Fertilization (F) ²			Mean	<i>p</i> - value F	<i>p</i> - value I	<i>p</i> - value I×F
	MF	OF	OF+MF				
	CP (%DM) ³				<0.01	<0.01	<0.01
C+M	7.5 ^{Ba}	5.2 ^{Ac}	6.1 ^{Cb}	6.3			
C+G	8.1 ^{Aa}	5.1 ^{Ab}	8.2 ^{Aa}	7.1			
C+G+M	7.9 ^{ABa}	4.9 ^{Ac}	7.2 ^{Bb}	6.7			
Mean	7.9	5.1	7.2				
	NDF (%DM) ⁴				<0.01	<0.01	<0.01
C+M	32.1 ^{Bb}	40.8 ^{Aa}	38.2 ^{Aa}	37.0			
C+G	33.5 ^{Bab}	36.5 ^{ABa}	30.4 ^{Bb}	33.5			
C+G+M	41.1 ^{Aa}	33.2 ^{Bb}	28.7 ^{Bb}	34.3			
Mean	35.6	36.8	32.4				

		ADF (%DM) ⁵			0.51	0.01	<0.01
C+M	11.7 ^{Aa}	13.2 ^{Aa}	13.7 ^{Aa}	12.8			
C+G	12.1 ^{Aa}	13.0 ^{Aa}	11.2 ^{Ba}	12.1			
C+G+M	13.4 ^{Aa}	9.7 ^{Bb}	10.7 ^{Bb}	11.3			
Mean	12.4	11.9	11.9				
		TDN (%DM) ⁶			<0.01	<0.01	<0.01
C+M	73.4 ^{Aa}	66.6 ^{Bb}	68.7 ^{Bb}	69.6			
C+G	72.7 ^{Aa}	69.4 ^{ABb}	74.8 ^{Aa}	72.3			
C+G+M	67.6 ^{Bc}	71.6 ^{Ab}	75.6 ^{Aa}	71.6			
Mean	71.2	69.2	73.0				
		EE (%DM) ⁷			0.51	0.44	0.73
C+M	2.0	2.0	2.1	2.04 ^A			
C+G	2.0	2.1	2.2	2.11 ^A			
C+G+M	2.1	2.2	2.1	2.12 ^A			
Mean	2.03 ^a	2.10 ^a	2.13 ^a				
		MM (%DM) ⁸			0.02	0.08	0.06
C+M	12.7	14.5	14.3	13.8 ^A			
C+G	12.7	14.3	12.2	13.1 ^A			
C+G+M	13.4	13.2	11.7	12.8 ^A			
Mean	12.9 ^{ab}	14.0 ^a	12.7 ^b				

898 ¹cactus pear and millet (C+M); cactus pear and gliricidia (C+G); cactus pear, gliricidia and millet
899 (C+G+M). ²Organic fertilization (OF); mineral fertilization (MF); organic and mineral fertilization
900 (OF+MF). ³CP = Crude Protein; ⁴NDF = Neutral Detergent Fiber; ⁵ADF = Acid Detergent Fiber; ⁶TDN =
901 Total Digestible Nutrients; ⁷EE = Ether Extract; ⁸MM = Mineral Matter. Lowercase and uppercase letters
902 compare means in the row and column, respectively, at the 5% level of significance according to the
903 Tukey's test.

904
905 In the C+M+G combination, NDF content reached 41.1%, significantly higher
906 (P<0.01) than in C+G (33.2%) and C+M (28.7%), with all crop combinations receiving
907 mineral fertilization. The C+M intercropping showed NDF and ADF contents of 38.2%
908 and 13.7%, respectively, both of which were higher (P≤0.01) than those recorded in
909 the C+G and C+M+G combinations.

910 The C+M intercropping under OF+MF management showed 68.7% TDN,
911 significantly lower (P<0.01) than in the C+G (74.8%) and C+M+G (75.6%)
912 combinations. The EE content of cactus pear was unaffected by the evaluated factors,
913 ranging from 2.03 to 2.13% DM. In contrast, MM was lower (P<0.01) under OF+MF
914 management compared with OF. Fertilization management also influenced CP
915 accumulation in millet (P<0.01), with OF resulting in 9.0% CP, while MF and OF+MF
916 yielded higher values of 10.5% (Table 4).

917

918 **Table 4.** Factors for the chemical composition of millet in the integrated system
919 subjected to different fertilization managements.

Intercropping (I) ¹	Fertilization (F) ²			Mean	p-value F	p-value I	p-value I×F
	MF	OF	OF+MF				
	CP (% DM)				< 0.01	0.20	0.69
C+M	10.5	9.3	10.9	10.2 ^A			
C+G+M	10.5	8.6	10.1	09.7 ^A			
Mean	10.5 ^a	9.0 ^b	10.5 ^a				
	NDF (%DM)				< 0.01	0.36	0.46
C+M	65.3	59.5	57.3	60.7 ^A			
C+G+M	62.5	60.7	54.7	59.4 ^A			
Mean	63.9 ^a	60.2 ^{ab}	56.0 ^b				
	ADF (%DM)				<0,01	0,37	0,35
C+M	31,5	28,6	28,5	29,5 ^A			
C+G+M	31,3	29,0	26,5	28,9 ^A			
Mean	31,4 ^a	28,8 ^b	27,5 ^b				
	TDN (%DM)				<0,01	0,45	0,42
C+M	52,5	55,8	58,0	55,4 ^A			
C+G+M	54,3	54,8	59,4	56,1 ^A			
Mean	53,4 ^b	55,3 ^b	58,7 ^a				
	EE (%DM)				0.95	0.35	0.08
C+M	2.3	2.5	2.4	2.4 ^A			
C+G+M	2.5	2.5	2.5	2.5 ^A			
Mean	2.4 ^a	2.5 ^a	2.5 ^a				
	MM (%DM)				0.24	0.31	0.08
C+M	5.8	5.9	6.5	6.1 ^A			
C+G+M	6.0	7.2	5.9	6.4 ^A			
Mean	5.9 ^a	6.6 ^a	6.3 ^a				

920 ¹cactus pear and millet (C+M); cactus pear and gliricidia (C+G); cactus pear, gliricidia and millet
921 (C+G+M). ²Organic fertilization (OF); mineral fertilization (MF); organic and mineral fertilization
922 (OF+MF). ³CP = Crude Protein; ⁴NDF = Neutral Detergent Fiber; ⁵ADF = Acid Detergent Fiber; ⁶TDN =
923 Total Digestible Nutrients; ⁷EE = Ether Extract; ⁸MM = Mineral Matter. Lowercase and uppercase letters
924 compare means in the row and column, respectively, at the 5% level of significance according to the
925 Tukey's test.
926

927 Millet exhibited lower NDF content under OF+MF management compared to
928 MF. ADF increased to 31.4% under MF management, while TDN was higher (P<0.01)
929 with OF+MF, reaching 58.7%. An effect of interaction (P=0.01) was observed on the
930 EE content of gliricidia, with the C+G and C+G+M combinations showing values of
931 2.6% and 3.0%, respectively (Table 5).
932

933 **Table 5.** Factors for the chemical composition of gliricidia in the integrated system
934 subjected to different fertilization managements.

Intercropping (I) ¹	Fertilization (F) ²			Mean	p-value F	p-value I	p-value I×F
	MF	OF	OF+MF				

		CP (%DM) ³			<0.01	0.75	0.15
C+G	13.8	13.6	16.1	14.5 ^A			
C+G+M	14.2	13.2	16.1	14.5 ^A			
Mean	14.0 ^b	13.4 ^c	16.1 ^a				
		NDF (%DM) ⁴			0.44	0.91	0.16
C+G	48.9	46.1	48.1	47.7 ^A			
C+G+M	45.5	48.2	49.7	47.8 ^A			
Mean	47.2 ^a	47.2 ^a	48.9 ^a				
		ADF (%DM) ⁵			0.68	0.22	0.64
C+G	28.0	27.7	28.1	27.9 ^A			
C+G+M	26.0	27.5	27.5	27.0 ^A			
Mean	27.0 ^a	27.6 ^a	27.8 ^a				
		TDN (%DM) ⁶			0.94	0.95	0.12
C+G	64.9	66.7	66.5	66.0 ^A			
C+G+M	67.4	65.1	65.4	66.0 ^A			
Mean	66.2 ^a	65.9 ^a	65.9 ^a				
		EE (%DM) ⁷			0.97	0.41	0.01
C+G	2.6 ^{Ba}	2.9 ^{Aa}	2.7 ^{Aa}	2.7			
C+G+M	3.0 ^{Aa}	2.7 ^{Aa}	2.7 ^{Aa}	2.8			
Mean	2.8	2.8	2.7				
		MM (%DM) ⁸			0.35	0.59	0.29
C+G	5.8	5.4	5.3	5.5 ^A			
C+G+M	5.2	5.4	5.3	5.3 ^A			
Mean	5.5 ^a	5.4 ^a	5.3 ^a				

935 ¹cactus pear and millet (C+M); cactus pear and gliricidia (C+G); cactus pear, gliricidia and millet
936 (C+G+M). ²Organic fertilization (OF); mineral fertilization (MF); organic and mineral fertilization
937 (OF+MF). ³CP = Crude Protein; ⁴NDF = Neutral Detergent Fiber; ⁵ADF = Acid Detergent Fiber; ⁶TDN =
938 Total Digestible Nutrients; ⁷EE = Ether Extract; ⁸MM = Mineral Matter. Lowercase and uppercase letters
939 compare means in the row and column, respectively, at the 5% level of significance according to the
940 Tukey's test.

941
942 No significant differences ($P>0.05$) were observed among the evaluated
943 intercropping systems for CP, NDF, ADF, TDN, EE, or MM in gliricidia. Fertilization
944 management also had no effect ($P>0.05$) on NDF, ADF, TDN, or MM. However, CP
945 content differed significantly ($P<0.01$) among fertilization managements, with gliricidia
946 accumulating 16.1% under OF+MF, followed by 14.0% under MF and 13.4% under
947 OF.

948 CPE and TDNE differed significantly ($P<0.05$), with the lowest exports observed
949 in the C+M intercropping (Table 6). Among fertilization managements, differences
950 ($P<0.05$) were found only for CFM, TFM, CPE, and TDNE, with the highest values
951 recorded under OF+MF.

952
953 **Table 6.** Factors for forage mass, crude protein exports and total digestible nutrients
954 of forage species in integrated systems subjected to different fertilization management.

Intercropping (I) ¹	Fertilization (F) ²			Mean	p-value F	p-value I	p-value I×F
	MF	OF	OF+MF				
Cactus Pear Forage Mass (CFM, ton ha ⁻¹)					<0.01	0.68	0.10
C+M	9.32	8.35	15.68	11.12 ^A			
C+G	11.84	11.20	17.04	13.36 ^A			
C+G+M	11.25	7.21	13.29	10.58 ^A			
Mean	10.80 ^b	8.92 ^b	15.34 ^a				
Millet Forage Mass (MFM, ton ha ⁻¹)					0.18	0.14	0.18
C+M	0.44	0.73	0.55	0.57 ^A			
C+G+M	0.38	0.41	0.58	0.46 ^A			
Mean	0.41 ^a	0.57 ^a	0.57 ^a				
Gliricidia Forage Mass (GFM, ton ha ⁻¹)					0.37	0.76	0.67
C+G	1.04	1.04	1.16	1.08 ^A			
C+G+M	0.91	1.04	1.46	1.14 ^A			
Mean	0.97 ^a	1.04 ^a	1.31 ^a				
Total Forage Mass (TFM, ton ha ⁻¹)					<0.01	0.12	0.78
C+M	9.77	9.08	16.23	11.69 ^A			
C+G	12.87	12.24	18.20	14.44 ^A			
C+G+M	12.54	8.66	15.33	12.77 ^A			
Mean	11.73 ^b	10.0 ^b	16.59 ^a				
Total CP export (TCPE, ton ha ⁻¹)					<0.01	<0.01	0.57
C+M	0.74	0.51	1.03	0.76 ^B			
C+G	1.11	0.72	1.59	1.14 ^A			
C+G+M	1.06	0.53	1.25	0.95 ^{AB}			
Mean	0.97 ^b	0.59 ^c	1.29 ^a				
Total TDN Export (TDNE, ton ha ⁻¹)					<0.01	0.04	0.96
C+M	7.07	5.95	11.10	8.04 ^B			
C+G	9.28	8.52	13.53	10.46 ^A			
C+G+M	8.40	6.09	11.35	8.61 ^{AB}			
Mean	8.25 ^b	6.88 ^b	11.99 ^a				

955 ¹cactus pear and millet (C+M); cactus pear and gliricidia (C+G); cactus pear, gliricidia and millet
956 (C+G+M). ²Organic fertilization (OF); mineral fertilization (MF); organic and mineral fertilization
957 (OF+MF). Lowercase and uppercase letters compare means in the row and column, respectively, at the
958 5% level of significance according to the Tukey's test.

959

960 DISCUSSION

961 Cactus pear proved to be demanding in nutrients and moisture, showing the
962 best performance under OF+MF management, with plants reaching 84.6 cm in height
963 and producing 15.8 cladodes (Table 2). Similar results were reported by Santos Neto
964 et al. (2023), who observed an average height of 80 cm and 12 cladodes per plant in
965 *Opuntia stricta* cv. Orelha de Elefante Mexicana grown in an integrated system in the
966 Brazilian Savannah. Likewise, Leite et al. (2018) found that mineral fertilization
967 significantly influences the height and number of cladodes in cactus pear. These

968 findings indicate that cactus pear is a highly plastic species, capable of high
969 productivity in fertile soils. It is considered nutrient-demanding and competitive in
970 integrated systems when its requirements for pH, mineral availability, moisture, and
971 soil organic matter are met (Kumar et al., 2022; Souza et al., 2022).

972 The height of millet and gliricidia were also higher under OF+MF management
973 and presented numerically higher MFM and GFM (Table 6), but without differences.
974 However, it is important to highlight that the plant population density in millet was lower
975 under MF (Table 2), but without compromising MFM production. Therefore, MF
976 positively influenced millet growth and probably caused an increase in tiller weight and
977 size.

978 Millet and gliricidia have distinct physiological mechanisms; however, being
979 hardy and well-adapted species, they exhibited similar RCI values, an indicator of leaf
980 chlorophyll content and, consequently, photosynthetic capacity. All fertilization
981 strategies, organic fertilizer, mineral fertilizer, and OF+MF, were sufficient to meet the
982 nutritional requirements of both species in the integrated systems.

983 According to Liu et al. (2023), pearl millet, a *Poaceae* species adapted to
984 intercropping and low-fertility soils, can be nitrogen-demanding in integrated systems
985 for grain and forage production, assimilating nitrogen at rates up to 225 kg ha⁻¹.
986 Consequently, cactus pear experienced competition with pearl millet in the C+M
987 intercropping, resulting in reduced nitrogen assimilation compared to C+G. This
988 competition under OF+MF management induced stress in cactus pear, increasing NDF
989 and ADF levels while decreasing TDN. These effects highlight how pearl millet,
990 particularly during flowering and fruiting stages under adequate nutrient and moisture
991 conditions, influenced the chemical composition of cactus pear.

992 In the C+M+G intercropping, cactus pear exhibited higher TDN under OF+MF
993 management, attributed to increased CP accumulation and reduced NDF content
994 (Magalhães et al., 2021). These factors are important because they directly influence
995 the effective degradability of CP and NDF, which are 58% and 62%, respectively
996 (Gomes et al., 2023), indicating that cactus pear's NDF is a high-quality nutrient
997 (Magalhães et al., 2021). Additionally, the C+M+G intercropping showed a reduction
998 in ADF, an indigestible and undesirable forage fraction (Gomes et al., 2023).

999 Cactus pear exhibited higher MM under the OF management, likely due to
1000 concentration and dilution effects. Lower CFM accumulation in this treatment
1001 concentrates minerals such as potassium and calcium, thereby increasing MM.

1002 Conversely, when CFM accumulation is high, a dilution effect occurs, leading to a
1003 decrease in MM (Barros et al., 2025; Matos Pessoa et al., 2026).

1004 The chemical composition of millet was influenced by fertilization management,
1005 highlighting its nutrient demand, particularly for nitrogen. Nitrogen supply in the
1006 integrated OF+MF system increased CP and TDN content while reducing NDF and
1007 ADF accumulation. However, millet naturally has high levels of NDF and ADF, which
1008 are directly associated with lower forage digestibility in the integrated C+M system,
1009 leading to a decrease in TDN in this intercropping system.

1010 Gliricidia fixes nitrogen in the soil through its roots via symbiosis with *Rhizobium*
1011 bacteria (Herrerangulo et al., 2023), resulting in low nitrogen fertilization requirements
1012 (Sá et al., 2021). The increased CP content observed in gliricidia under MF and
1013 OF+MF treatments was partly due to higher levels of non-protein nitrogen (Carelli et
1014 al., 1981).

1015 EE content in gliricidia ranged from 2.6 to 3.0% in the C+G and C+G+M
1016 systems, which may be attributed to contaminants such as resins and pigments
1017 introduced during the extraction process (Galeriani and Cosmo, 2020).

1018 The presence of gliricidia in the C+G and C+G+M systems contributed to
1019 increased accumulation of CP and TDN, as this forage species has low nitrogen
1020 demand, allowing nutrients supplied by MF and OF+MF to be more effectively utilized
1021 by cactus pear and millet. Gliricidia also demonstrated strong tolerance to
1022 intercropping with both cactus pear and millet, maintaining consistent GFM values
1023 regardless of the system. These values align with those reported by Saraiva et al.
1024 (2022), who recorded 0.9 tons ha⁻¹ in cactus pear intercropped with gliricidia under
1025 various organic fertilization regimes. Consequently, CPE and TDNE were higher in the
1026 C+G and C+G+M systems, reflecting gliricidia's chemical composition and its
1027 facilitative effect on the growth and productivity of companion species without
1028 negatively impacting their forage quality. In contrast, the C+M intercropping exhibited
1029 lower CPE and TDNE, as millet's naturally high NDF and ADF content and strong
1030 nitrogen competition negatively affected cactus pear's chemical composition,
1031 decreasing CP and increasing NDF. Alves et al. (2020) also reported millet's low MFM
1032 and competitive nature, which limits productivity gains in C+M compared to
1033 monoculture. Nevertheless, despite its competitiveness, millet offers advantages when
1034 intercropped with cactus pear, outperforming monoculture systems (Souza et al., 2022;
1035 Souza et al., 2023).

1036 The combined use of organic and mineral fertilization synchronizes nutrient
1037 supply with the nutritional demands of the intercropping system, promoting increased
1038 production of CFM, TFM, CPE, and TDNE.

1039

1040 CONCLUSION

1041 The combined use of organic and mineral fertilizers enhances forage mass
1042 production, crude protein export, and total digestible nutrients in integrated systems.
1043 This management also promotes greater height, cladode number, and forage mass in
1044 cactus pear.

1045 Mineral fertilization, alone or combined with organic fertilization, enhances the
1046 chemical composition of species grown in integrated forage production systems,
1047 particularly improving crude protein, neutral detergent fiber, and total digestible
1048 nutrients.

1049 Forage mass production was similar across the integrated systems; however,
1050 the cactus pear and gliricidia (C+G), as well as the cactus pear, gliricidia, and millet
1051 (C+G+M) intercropping, exported higher amounts of crude protein and total digestible
1052 nutrients.

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CHAPTER III

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EVALUATION OF MIXED SILAGES FROM INTEGRATED FORAGE PRODUCTION SYSTEMS

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1227 **Abstract:** The use of cactus pear (*Opuntia ficus-indica*), millet (*Pennisetum glaucum*),
1228 and gliricidia (*Gliricidia sepium*) in integrated systems for the production of mixed silage
1229 may represent a viable strategy for supplying forage. This study aimed to evaluate the
1230 chemical composition, microbiological characteristics, and quality parameters of mixed
1231 silages composed of cactus pear, millet, and/or gliricidia grown in an integrated system
1232 subjected to organic and mineral fertilization management. All forage biomass
1233 produced by each species within the integrated system area was ensiled in order to
1234 simulate real production conditions. Nine experimental treatments were established,
1235 each with four replications, using 3.6 L laboratory silos. A completely randomized
1236 design was adopted, and treatment means were compared using the Scott-Knott test
1237 at a 5% significance level. The evaluated silages differed ($P < 0.05$) in dry matter
1238 content, which ranged from 5.98% to 13.45%. Significant differences were also
1239 observed for pH, soluble carbohydrates, and organic acid concentrations. No
1240 differences ($P > 0.05$) were detected for ammonia nitrogen or aerobic stability among
1241 treatments. The aerobic stability of all silages lasted only 3 hours after silo opening. It
1242 is concluded that integrated systems combining cactus pear and gliricidia under
1243 organic fertilization (CP+G+OF), mineral fertilization (CP+G+MF), or both
1244 (CP+G+MF+OF), as well as systems combining cactus pear, millet, and gliricidia under
1245 mineral (CP+M+G+MF) or mineral plus organic fertilization (CP+M+G+MF+OF),
1246 produce forage that, when ensiled, yields superior fermentative quality parameters,
1247 higher organic acid concentrations, and greater dry matter recovery.

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Keywords: acetic acid, butyric acid, lactic acid, aerobic stability, effluent losses, gas losses

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INTRODUCTION

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Integrated forage-production systems represent a more efficient strategy for land use, aiming to cultivate more than one plant species within the same area and provide diverse feed resources that may be used directly by animals or harvested for conservation and later utilization (Miranda, 2018; Cavalcante, 2020), primarily as

1257 silage. In this context, understanding the agronomic characteristics of forage crops,
1258 implementing appropriate mineral and organic fertilization regimes, and diversifying
1259 plant species within integrated systems are essential strategies to maximize
1260 productivity (FAO, 2022). Additionally, ruminant animals require balanced supplies of
1261 energy, protein, and minerals, which are best fulfilled through the combination of
1262 multiple forage species (Miranda, 2018).

1263 The use of cactus pear (*Opuntia ficus-indica*), millet (*Pennisetum glaucum*), and
1264 gliricidia (*Gliricidia sepium*) in integrated forage-production systems may be an
1265 advantageous option for ruminant feeding, as these species are well adapted to
1266 tropical climates and present complementary characteristics for intercropping. When
1267 combined, they can meet the nutritional requirements of ruminants, offering a strategic
1268 and sustainable approach that reduces dependency on external inputs (Miranda, 2018;
1269 Cavalcante, 2020) and contributes to more environmentally sustainable agricultural
1270 systems (FAO, 2022).

1271 Forage conservation through ensiling is a viable strategy to ensure consistent
1272 feed supply throughout the year, particularly during critical periods when pasture
1273 availability is limited (Silva et al., 2020; Sá et al., 2021). Mixed silage production, which
1274 consists of ensiling two or more forage species, aims to preserve the nutritional value
1275 of the crops and improve fermentative processes, thereby minimizing losses
1276 throughout the ensiling stages (Brito et al., 2020; Sá et al., 2020; Oliveira et al., 2023).
1277 Due to its high moisture content, silage made exclusively from cactus pear (Cactaceae)
1278 poses challenges, including low dry matter recovery and substantial effluent losses
1279 (Silva et al., 2020; Oliveira et al., 2023), which reinforces the relevance of using this
1280 species as part of integrated forage systems for mixed-silage production.

1281 This study was designed under the hypothesis that mixed silages composed of
1282 nonconventional forage species would exhibit acceptable levels of losses, chemical
1283 composition, microbial ecology, organic acid profiles, and overall quality parameters.
1284 Therefore, the objective was to evaluate the chemical composition, microbiological
1285 characteristics, and quality parameters of mixed silages of cactus pear, millet, and/or
1286 gliricidia derived from an integrated system subjected to organic and mineral
1287 fertilization regimes.

1288

1289 **MATERIALS AND METHODS**

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1291 **Location and establishment of the integrated forage production system**

1292 The experiment was conducted at the Federal Institute of Education, Science
1293 and Technology of Piauí (Instituto Federal do Piauí - IFPI), located in Valença do
1294 Piauí, Piauí, Brazil (6°25'23.5"S, 41°45'02.9"W). According to Köppen's climate
1295 classification, the region has an Aw-type climate (Köppen, 1936), characterized as
1296 hot tropical, with minimum temperatures of 26 °C and maximum temperatures of 35
1297 °C. The mean annual rainfall is 1,103 mm, ranging from 800 to 1,400 mm, with 5 to
1298 6 months of concentrated precipitation followed by a pronounced dry season
1299 (Medeiros et al., 2020).

1300 Nine integrated production systems were established in 36 plots, each with
1301 a useful area of 12 m² (6 m × 2 m), using different combinations of cactus pear
1302 (*Opuntia ficus-indica*), millet (*Pennisetum glaucum*), and gliricidia (*Gliricidia*
1303 *sepium*). Each integrated system was associated with a specific fertilization
1304 management strategy (organic or mineral). The integrated systems consisted of:

1305

- 1306 1. Cactus pear + millet + mineral fertilization (CP+M+MF);
- 1307 2. Cactus pear + millet + organic fertilization (CP+M+OF);
- 1308 3. Cactus pear + millet + mineral fertilization + organic fertilization (CP+M+MF+OF);
- 1309 4. Cactus pear + gliricidia + mineral fertilization (CP+G+MF);
- 1310 5. Cactus pear + gliricidia + organic fertilization (CP+G+OF);
- 1311 6. Cactus pear + gliricidia + mineral fertilization + organic fertilization
1312 (CP+G+MF+OF);
- 1313 7. Cactus pear + millet + gliricidia + mineral fertilization (CP+M+G+MF);
- 1314 8. Cactus pear + millet + gliricidia + organic fertilization (CP+M+G+OF);
- 1315 9. Cactus pear + millet + gliricidia + mineral fertilization + organic fertilization
1316 (CP+M+G+MF+OF).

1317 Following soil analysis, liming was performed to increase base saturation.
1318 The area was then disked, and fertilization treatments were applied according to
1319 each system: organic fertilization (OF), mineral fertilization (MF), and combined
1320 mineral + organic fertilization (MF+OF). Organic fertilization consisted of a single
1321 topdressing application equivalent to 35,000 kg ha⁻¹ year⁻¹ of a mixture of cattle
1322 manure and poultry litter (broiler bedding) at a 1:1 ratio on a dry weight basis.
1323 Mineral fertilization consisted of applying 100 kg ha⁻¹ of P₂O₅ (70 kg at planting and
1324 30 kg as topdressing using single superphosphate), 70 kg ha⁻¹ of K₂O as

1325 topdressing (potassium chloride), and 200 kg ha⁻¹ of nitrogen applied in three split
 1326 topdressings (urea). The combined treatment (MF+OF) consisted of the full
 1327 application of both mineral and organic fertilization regimes.

1328 Gliricidia was established using 20-cm stem cuttings, planted at 6 m × 0.5 m
 1329 spacing. Cactus pear was planted between the gliricidia rows using mature
 1330 cladodes buried halfway into the soil at 1.5 m × 0.2 m spacing. Millet was sown in
 1331 continuous rows between the cactus pear lines, with 0.7 m row spacing. Millet was
 1332 harvested by cutting at ground level. Cactus pear was harvested while preserving
 1333 the primary cladodes, and gliricidia was harvested at 50 cm height above the soil
 1334 surface.

1335

1336 **Morphological composition of forage**

1337 All forage biomass produced from each species within the integrated system
 1338 plots was ensiled to simulate real-world producer conditions. The proportional
 1339 contribution of each forage species originating from the integrated systems is
 1340 presented in Table 1.

1341

1342 **Table 1.** Botanical composition of forage harvested at the moment of ensiling

Integrated system ¹	Cactus pear	Millet	Gliricidia	Cactus pear	Millet	Gliricidia
	As Fed (%)			Dry Matter (%)		
(1)CP+M+MF	97	3	0	89	11	0
(2)CP+M+OF	94	6	0	80	20	0
(3)CP+M+MF+OF	98	2	0	94	6	0
(4)CP+G+MF	96	0	4	83	0	17
(5)CP+G+OF	91	0	9	65	0	35
(6)CP+G+MF+OF	98	0	2	92	0	8
(7)CP+M+G+MF	97	1	2	85	3	12
(8)CP+M+G+OF	89	3	8	62	9	29
(9)CP+M+G+MF+OF	95	2	3	83	7	9

1343 ¹ CP=Cactus pear; M=Millet; MF=Mineral fertilization; G=Gliricidia; OF=Organic fertilization;

1344

1345 **Gas and effluent losses, and dry matter recovery**

1346 After 120 days, the silos were opened for the evaluation of gas losses,
 1347 effluent losses, and dry matter recovery, according to the following equations:

1348 **Gas losses:**

1349
$$GL = \frac{FWc - FWo}{(IFW \times DM_{IFW})} \times 100$$

1350

1351 where GL = gas losses (% DM); FW_c = total weight of the filled silo at closing (kg);
1352 FW_o = total weight of the filled silo at opening (kg); IFW = initial forage weight (kg);
1353 DM_{IFW} = dry matter content of the forage at ensiling (Jobim et al., 2007).

1354 **Effluent losses:**

1356
$$EL = \frac{(EW_o - EW_c)}{FW_{\text{fresh}}} \times 1000$$

1355

1357 where EL = effluent losses (kg ton⁻¹ of fresh forage ensiled); EW_o = weight of the
1358 empty silo plus sand at opening (kg); EW_c = weight of the empty silo plus sand at
1359 closing (kg); FW_{fresh} = weight of the fresh forage ensiled (Jobim et al., 2007).

1360 **Dry matter recovery:**

1362
$$DMR = \frac{(FW_o \times DM_o)}{(FW_c \times DM_c)} \times 100$$

1361

1363 where DMR = dry matter recovery rate (% DM); FW_c = forage mass at closing (kg);
1364 DM_c = dry matter content at closing (%); FW_o = forage mass at opening (kg); DM_o =
1365 dry matter content at opening (%) (Jobim et al., 2007).

1366 The density of the ensiled forage was also determined using the equation:

1368
$$DF = \frac{FW_{\text{ensiled}}}{V_{\text{silo}}}$$

1367

1369 where DF = density of ensiled forage (kg m⁻³); FW_{ensiled} = mass of ensiled forage;
1370 and V_{silo} = silo volume.

1371

1372 **Chemical composition of forage and silage parameters**

1373 Cactus pear was chopped until reaching a mucilaginous consistency, whereas
1374 millet and gliricidia were processed to obtain a particle size of approximately 4 mm. All
1375 forages (cactus pear, millet, and gliricidia) were harvested on the same date (July 7,
1376 2023), at 720, 70, and 70 days after planting, respectively. The forages from each
1377 integrated cultivation system were thoroughly homogenized and ensiled in
1378 experimental silos, which were properly compacted, sealed, and stored for 120 days.

1379 The silos consisted of transparent plastic buckets with a capacity of 3.6 liters,
1380 equipped with lids fitted with Bunsen valves. A 1-kg layer of sand was placed at the

1381 bottom of each bucket and separated from the ensiled forage using a nonwoven fabric
 1382 (TNT, 100 g/m²).

1383 Representative samples of the homogenized forage from each integrated
 1384 system were collected at the time of ensiling, labeled, and sent to the Animal Nutrition
 1385 Research Laboratory (LAPEN) at the Federal University of Piauí (UFPI) for analysis.
 1386 The results of these analyses are presented in Table 2.

1387

1388 **Table 2.** Chemical composition of the forage harvested at the moment of ensiling.

Silages ¹	DM ²	MM ³	TDN ₄	NDF ₅	ADF ₆	CP ₇	EE ⁸	SC ₉	SC ¹⁰
(1)CP+M+MF	7.79	12.85	68.79	38.44	17.54	6.64	1.43	1.43	17.18
(2)CP+M+OF	8.46	12.50	69.29	36.81	17.68	5.30	1.37	1.37	14.76
(3)CP+M+MF+OF	6.68	12.54	71.35	34.46	16.72	6.39	1.41	1.41	14.94
(4)CP+G+MF	9.46	10.80	72.51	32.89	16.38	6.65	2.32	2.32	20.29
(5)CP+G+OF	13.46	7.81	66.16	42.28	22.13	6.51	2.79	2.79	15.90
(6)CP+G+MF+OF	9.79	9.51	71.53	34.54	20.12	6.93	2.13	2.13	16.13
(7)CP+M+G+MF	10.14	8.25	70.23	36.15	19.70	6.43	2.52	2.52	19.59
(8)CP+M+G+OF	12.09	12.10	64.54	44.44	23.09	6.10	3.08	3.08	14.98
(9)CP+M+G+MF+OF	9.64	9.46	69.76	36.83	20.06	6.38	2.19	2.19	16.17

1389 ¹ CP=Cactus pear; M=Millet; MF=Mineral fertilization; G=Gliricidia; OF=Organic fertilization; ² DM=Dry
 1390 matter of silage (% as fed); ³ MM=Mineral matter; ⁴ TDN=Total digestible nutrients; ⁵ NDF=Neutral
 1391 detergent fiber; ⁶ ADF=Acid detergent fiber; ⁷ CP=Crude protein; ⁸ EE=Ether extract; ^{9, 10} CS=Soluble
 1392 carbohydrates (% as fed and dry matter)

1393

1394 Chemical composition analyses of the forage and silage were carried out by
 1395 determining dry matter (DM) at 105 °C, crude protein (CP; method 988.05), and ash
 1396 (mineral matter, MM; method 942.05), following AOAC procedures (AOAC, 2012).
 1397 Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were analyzed according
 1398 to the methodology described by Mertens et al. (2002), adapted for an autoclave
 1399 system (105 °C for 60 min) as proposed by Barbosa et al. (2015), using nonwoven
 1400 fabric (TNT, 100 g/m²) bags measuring 4 × 5 cm with 100-µm porosity. Ether extract
 1401 (EE) was determined using solvent extraction (ether) in a Soxhlet-type extractor
 1402 following the Randall method (Method G-005/2). Total digestible nutrients (TDN) were
 1403 estimated according to Cappelle et al. (2001) for forages, using the equation:

$$1404 \quad \text{TDN}(\%) = 91.6086 - 0.669233 \times (\text{NDF}) + 0.437932 \times (\text{CP})$$

1405

1406 Total soluble carbohydrates (SC) were determined using the concentrated
 1407 sulfuric acid method described by Dubois et al. (1956), with adaptations from Corsato
 1408 et al. (2008). SC were extracted using an ethanol solution, and absorbance readings

1409 were taken at 490 nm in a digital spectrophotometer. A standard curve was prepared
1410 using D-glucose at different concentrations (Dubois et al., 1956).

1411 Ammonia nitrogen/total nitrogen (NH₃-N/TN) in the silages was determined from
1412 silage juice. A 25-g sample of silage from each silo was mixed with 200 mL of 0.2 N
1413 sulfuric acid, placed in sealed Falcon tubes, and kept under refrigeration for 48 hours
1414 to solubilize NH₃-N. The material was then filtered through filter paper and distilled with
1415 2 N potassium hydroxide (KOH) using the Kjeldahl method, followed by titration with
1416 0.1 N hydrochloric acid (HCl), as described by Bolsen et al. (1992).

1417 To determine pH, 10 g of silage were mixed with 90 mL of distilled water and
1418 allowed to stand for one hour, after which readings were taken using a digital pH meter
1419 (Instrutermh, São Paulo, Brazil) following Bolsen et al. (1992).

1420 Buffering capacity was determined according to Playne and McDonald (1966).
1421 A 15-g silage sample was macerated and mixed with 250 mL of distilled water,
1422 homogenized in a blender, transferred to plastic containers, and measured using a
1423 digital pH meter. Calculations were performed according to the recommendations of
1424 Mizubutti et al. (2009).

1425

1426 **Silage microbiology**

1427 Silage sample analyses were conducted at the Forage Science Laboratory
1428 (LABFOR) of the Federal University of Piau , in Teresina, Piau , Brazil. For each
1429 analysis, 25 g of fresh silage were collected, to which 90 mL of distilled water were
1430 added. The mixture was homogenized in a blender for approximately 1 minute.
1431 Subsequently, 1 mL of the homogenate was pipetted into Petri dishes corresponding
1432 to the 10⁻¹, 10⁻², 10⁻³, 10⁻⁴, 10⁻⁵, and 10⁻⁶ dilutions.

1433 Plating was performed in duplicate for each culture medium. Microbial
1434 populations were quantified using selective culture techniques under anaerobic
1435 conditions. The following media were used: Rogosa agar for enumeration of lactic acid
1436 bacteria (LAB), after incubation for 48 hours at 37 °C; acidified Potato Dextrose Agar
1437 (PDA), adjusted with 1% tartaric acid, for enumeration of filamentous fungi and yeasts,
1438 after 48 hours of incubation at room temperature; and Brilliant Green Bile Agar for
1439 enumeration of enterobacteria, after 24 hours of incubation at 35 °C.

1440 Petri dishes were incubated in a biochemical oxygen demand (BOD) incubator.
1441 Only plates presenting 30 to 300 colony-forming units (CFU) were considered
1442 countable, and results were expressed as the mean CFU of the selected dilution.

1443

1444 **Determination of organic acids in silage**

1445 The concentrations of lactic, acetic, propionic, and butyric acids in the silages
1446 were determined using high-performance liquid chromatography (HPLC), following the
1447 procedure described by Kung and Ranjit (2001). A 10 mL aliquot of each sample was
1448 diluted to 10% in distilled water, acidified with 50% H₂SO₄, and filtered through
1449 Whatman filter paper. To 2 mL of the filtrate, 1 mL of 20% metaphosphoric acid and
1450 0.2 mL of 0.1% phenol were added. The samples were then centrifuged, and the
1451 supernatant was used for the determination of organic acids (lactic, acetic, propionic,
1452 and butyric) by high-performance liquid chromatography. Analyses were performed
1453 using a Shimadzu LCMS-2020 system (UFLC model) equipped with an SIL-20A
1454 autosampler.

1455

1456 **Aerobic stability break**

1457 After opening the silos, the entire silage mass was removed and homogenized
1458 on a plastic tray. Approximately 2 kg of silage were then placed back into the opened
1459 silos, which were stored in a climate-controlled chamber at 25 ± 0.1°C to evaluate
1460 aerobic stability. Silage temperatures were recorded every 2 hours for 96 hours,
1461 following Johnson et al. (2002). Ambient temperature was regulated by the chamber
1462 thermostat and monitored using suspended thermometers. Internal silage temperature
1463 was measured by inserting an INCOTERM® thermometer 10 cm into the center of the
1464 silage mass. Aerobic stability was defined as the time elapsed after silo opening until
1465 the silage temperature increased by 2°C above the chamber temperature (25 ± 1.0°C),
1466 according to Jobim et al. (2007).

1467

1468 **Statistical analyses**

1469 The data were subjected to analysis of variance (ANOVA). Normality was
1470 assessed using the Shapiro-Wilk test, and homogeneity of variances was verified using
1471 Bartlett's test. Data on chemical composition, silage quality parameters, organic acids,
1472 silage microbiology, aerobic stability, and losses due to gas, effluent, and dry matter
1473 recovery were analyzed using a completely randomized design with nine treatments
1474 and four replicates, according to the following statistical model:

1475

$$y_{ij} = \mu + t_j + e_{ij}$$

1476 where y_{ij} is the observed value of the j^{th} treatment in the i^{th} replicate; μ is the overall
 1477 mean; t_j is the effect of the j^{th} treatment; and e_{ij} is the random error associated with
 1478 the i^{th} replicate of the j^{th} treatment. Means were compared using the Scott-Knott test at
 1479 a 5% significance level ($P \leq 0.05$). All analyses were performed using SISVAR software
 1480 (Ferreira, 2011).

1481
 1482 **RESULTS**

1483 A significant effect ($P < 0.05$) was observed among the evaluated silages for gas
 1484 losses, effluent losses, dry matter recovery, and silage density (Table 3).

1485
 1486 **Table 3.** Gas losses (GL), effluent losses (EL), dry matter recovery (DMR), and silage
 1487 density (SD) of mixed silages of cactus pear, millet, and/or gliricidia subjected to
 1488 organic and mineral fertilization management.

Silages ¹	GL (%)	EL (kg ton ⁻¹)	DMR (%DM)	SD (kg m ⁻³)
(1)CP+M+MF	4.99 ^a	82.96 ^a	88.17 ^a	665.8 ^a
(2)CP+M+OF	2.81 ^b	65.64 ^b	90.94 ^a	580.2 ^c
(3)CP+M+MF+OF	2.92 ^b	80.45 ^a	77.42 ^b	588.8 ^c
(4)CP+G+MF	3.16 ^b	61.11 ^b	85.47 ^a	589.2 ^c
(5)CP+G+OF	2.75 ^b	57.44 ^b	91.55 ^a	602.0 ^c
(6)CP+G+MF+OF	1.29 ^c	71.44 ^a	89.85 ^a	617.0 ^c
(7)CP+M+G+MF	3.22 ^b	80.65 ^a	87.18 ^a	612.0 ^c
(8)CP+M+G+OF	1.58 ^c	76.66 ^a	82.96 ^b	623.0 ^b
(9)CP+M+G+MF+OF	1.73 ^c	76.02 ^a	90.16 ^a	633.6 ^b
SEM ²	0.42	3.61	2.50	10.53
<i>p-value</i>	0.01	<0.01	0.01	<0.01
CV (%) ³	29.54	11.15	6.42	3.85

1489 ¹ CP=Cactus pear; M=Millet; MF=Mineral fertilization; G=Gliricidia; OF=Organic fertilization; ²
 1490 SEM=Standard Error of the Mean; ³CV=Coefficient of Variation; Equal letters in the column indicate no
 1491 statistical difference between means by the Scott- Knott test ($p < 0.05$).

1492

1493 The evaluated silages differed ($P<0.05$) for all variables except ammonia nitrogen. Dry matter content was low across all mixed
 1494 silages, ranging from 5.98 to 13.45%. Silage (5) showed higher NDF, ADF, and CP concentrations, accompanied by lower TDN and
 1495 ash contents. In contrast, silage (4) presented higher TDN and lower NDF than silage (5) (Table 4).

1496

1497 **Table 4.** Chemical composition and quality parameters of mixed silages of cactus pear, millet, and/or gliricidia subjected to organic
 1498 and mineral fertilization management.

Silages ¹	MM ²	NDF ³	ADF ⁴	CP ⁵	EE ⁶	TDN ⁷	DM ⁸	pH ⁹	SC ¹⁰	BCAP ¹¹	N-HH ₃ ¹²
(1)CP+M+MF	12.51 ^b	40.94 ^c	16.5 ^d	7.00 ^b	1.60 ^b	67.27 ^c	7.91 ^d	3.94 ^c	7.66 ^a	112.0 ^b	4.66 ^a
(2)CP+M+OF	13.04 ^a	39.49 ^c	16.39 ^d	5.15 ^d	1.60 ^b	67.43 ^c	8.48 ^d	4.29 ^b	8.91 ^a	85.7 ^c	4.94 ^a
(3)CP+M+MF+OF	12.15 ^c	41.17 ^c	16.27 ^d	6.54 ^c	2.22 ^a	66.91 ^c	5.98 ^e	4.76 ^a	7.23 ^a	183.3 ^a	3.81 ^a
(4)CP+G+MF	9.80 ^f	37.05 ^d	16.50 ^d	7.80 ^a	2.53 ^a	70.24 ^a	8.91 ^d	3.93 ^c	3.49 ^b	80.0 ^c	4.01 ^a
(5)CP+G+OF	8.77 ^h	46.49 ^a	23.07 ^a	8.22 ^a	2.69 ^a	64.09 ^e	13.45 ^a	3.95 ^c	3.67 ^b	68.0 ^c	3.18 ^a
(6)CP+G+MF+OF	10.03 ^e	38.75 ^d	19.35 ^c	7.35 ^b	2.61 ^a	68.89 ^b	9.69 ^c	3.97 ^c	5.97 ^a	81.7 ^c	3.55 ^a
(7)CP+M+G+MF	8.79 ^h	40.44 ^c	19.37 ^c	7.94 ^a	2.04 ^b	68.02 ^c	9.93 ^c	3.74 ^c	7.91 ^a	69.2 ^c	3.93 ^a
(8)CP+M+G+OF	9.11 ^g	43.06 ^b	21.39 ^b	7.03 ^b	2.56 ^a	65.87 ^d	11.15 ^b	4.77 ^a	7.85 ^a	75.5 ^c	3.65 ^a
(9)CP+M+G+MF+OF	10.61 ^d	40.73 ^c	19.51 ^c	6.93 ^b	2.18 ^a	67.39 ^c	9.65 ^c	3.82 ^c	6.50 ^a	70.0 ^c	4.58 ^a
SEM ¹³	0.22	0.63	0.33	0.13	0.19	0.44	0.30	0.15	0.78	6.53	0.66
<i>p-value</i>	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.64
CV (%) ¹⁴	0.86	3.10	3.50	3.73	17.41	1.30	6.41	3.97	23.71	14.23	32.78

1499 ¹ CP=Cactus pear; M=Millet; MF=Mineral Fertilization; OF=Organic Fertilization; G=Gliricidia; ² MM=Mineral Matter; ³ NDF=Neutral Detergent Fiber; ⁴ ADF=Acid
 1500 Detergent Fiber; ⁵ CP=Crude Protein; ⁶ EE=Ether Extract; ⁷ TDN=Total Digestible Nutrients; ⁸ DM=Dry Matter as a percentage as fed (AF); ⁹ pH=Hydrogen Ion
 1501 Potential; ¹⁰ SC=Soluble Carbohydrates (%) in DM; ¹¹ BCAP=Buffer Capacity; ¹² N-HH₃ = Ammonia Nitrogen as a percentage of Total Nitrogen; ¹³ SEM=Standard
 1502 Error of the Mean; ¹⁴ CV(%)=Coefficient of Variation; Equal letters in the column show no statistically significant difference between means according to the
 1503 Scott- Knott test ($P\leq 0.05$).

Lactic acid bacteria (LAB) and molds/yeasts were detected in all evaluated silages. Silages (1), (2), (3), and (6) showed higher LAB counts ($P=0.01$) and lower mold/yeast counts ($P=0.02$) than silages (4), (5), and (7), indicating the antagonistic roles these microorganisms play within silage (Table 5).

Table 5. Counts of lactic acid bacteria (LAB), enterobacteria (ENT), yeasts (YEAST), and molds (MOLD) in mixed silages of cactus pear, millet, and/or gliricidia subjected to organic and mineral fertilization management.

Silages ¹	LAB	MOLD	YEAST
	log/CFU/g		
(1)CP+M+MF	3.68 ^b	3.74 ^a	1.04 ^a
(2)CP+M+OF	4.36 ^b	4.00 ^a	1.55 ^a
(3)CP+M+MF+OF	3.86 ^b	3.77 ^a	0.38 ^b
(4)CP+G+MF	4.91 ^a	2.93 ^b	0.0 ^b
(5)CP+G+OF	4.99 ^a	2.63 ^b	0.29 ^b
(6)CP+G+MF+OF	4.02 ^b	3.33 ^a	0.0 ^b
(7)CP+M+G+MF	4.55 ^a	3.99 ^a	1.09 ^a
(8)CP+M+G+OF	4.91 ^a	2.93 ^b	0.83 ^a
(9)CP+M+G+MF+OF	5.29 ^a	2.64 ^b	1.29 ^a
SEM ²	0.32	0.36	0.18
<i>p-value</i>	0.01	0.02	<0.01
CV (%) ³	23.05	34.16	76.89

¹ CP=Cactus pear; M=Millet; MF=Mineral fertilization; G=Gliricidia; OF=Organic fertilization; ² SEM=Standard Error of the Mean; ³ CV=Coefficient of Variation; Equal letters in the column indicate no statistical difference between means by the Scott- Knott test ($p<0.05$).

Significant differences ($P<0.05$) were observed among the silages for lactic, acetic, propionic, and butyric acid concentrations. Silages (1) and (3) showed excessively high levels of butyric acid, indicating deterioration and the presence of an unpleasant odor. In addition, silages (1), (3), and (8) exhibited lower lactic acid concentrations ($P <0.01$) (Table 6).

Table 6. Organic acid concentrations in mixed silages of cactus pear, millet, and/or gliricidia subjected to organic and mineral fertilization management.

Mixed silages	Acid			
	Lactic	Acetic	Propionic	Butyric
g kg DM ⁻¹ of silage				
(1)CP+M+MF	40.93 ^b	109.57 ^a	25.32 ^a	100.08 ^a
(2)CP+M+OF	74.37 ^a	27.02 ^d	8.01 ^b	39.88 ^b
(3)CP+M+MF+OF	35.56 ^b	78.90 ^b	11.19 ^b	96.25 ^a
(4)CP+G+MF	92.91 ^a	52.41 ^c	5.60 ^b	7.41 ^c
(5)CP+G+OF	107.67 ^a	44.45 ^c	4.19 ^b	15.81 ^c

(6)CP+G+MF+OF	99.99 ^a	55.53 ^c	7.60 ^b	5.28 ^c
(7)CP+M+G+MF	109.77 ^a	31.42 ^d	6.83 ^b	16.81 ^c
(8)CP+M+G+OF	35.74 ^b	36.33 ^d	7.03 ^b	9.58 ^c
(9)CP+M+G+MF+OF	101.39 ^a	30.53 ^d	3.33 ^b	2.53 ^c
SEM	10.66	3.68	1.49	7.62
<i>p-value</i>	<0.01	<0.01	<0.01	<0.01
CV (%)	23.81	12.34	29.32	40.51

SEM = Standard Error of the Mean; CV(%) = Coefficient of Variation; Equal letters in the column indicate no statistical difference between means by the Scott- Knott test ($p < 0.05$).

No significant differences were observed among the silages for the variables presented in Table 7. The time required for the silages to lose aerobic stability ranged from 2.5 to 3.0 hours after silo opening, accompanied by an increase in pH.

Table 7. Time required for aerobic stability break (ASB), pH, climate chamber temperature (CCT), and internal silage temperature (IT) in mixed silages of cactus pear, millet, and/or gliricidia subjected to organic and mineral fertilization management.

Silages ¹	ASB (hours)	IT (°C)	CCT (°C)	pH
(1)CP+M+MF	3.0 ^a	28.75 ^a	25.8	4.11 ^a
(2)CP+M+OF	3.0 ^a	27.50 ^a	25.1	4.22 ^a
(3)CP+M+MF+OF	2.5 ^a	27.50 ^a	24.3	4.56 ^a
(4)CP+G+MF	2.5 ^a	27.50 ^a	24.5	4.15 ^a
(5)CP+G+OF	2.5 ^a	27.75 ^a	24.9	4.25 ^a
(6)CP+G+MF+OF	2.5 ^a	27.75 ^a	25.3	4.00 ^a
(7)CP+M+G+MF	2.5 ^a	27.75 ^a	25.1	4.02 ^a
(8)CP+M+G+OF	2.5 ^a	28.25 ^a	25.1	4.56 ^a
(9)CP+M+G+MF+OF	2.5 ^a	28.50 ^a	25.1	3.94 ^a
SEM	0.52	0.27	-	0.19
<i>p-value</i>	0.99	0.11	-	0.27
CV (%)	39.69	1.92	-	9.31

¹ CP=Cactus pear; M=Millet; MF=Mineral fertilization; G=Gliricidia; OF=Organic fertilization; Equal letters in the column indicate no statistical difference between means by the Scott- Knott test ($p < 0.05$).

DISCUSSION

Gas losses were higher ($P=0.01$) in silage (1) (Table 3), mainly due to the activity of *Clostridium* spp., which produce butyric acid and CO₂. In this silage, it was also observed the development of *Propionibacterium* spp., microorganisms known to produce propionic acid and CO₂ (Souza et al., 2020), further contributing to the elevated gas losses. Conversely, the lower gas losses observed in silages (6), (8), and (9) (Table 3) may be attributed to their reduced butyric acid concentrations. Gas losses between 2 and 4% are considered acceptable (Ramos et al., 2021; Zimmer, 1980) and are associated with the anaerobic conditions inside the silo, particularly rapid

fermentations by enterobacteria, which consume soluble carbohydrates and release CO₂.

Effluent losses were high across treatments, primarily due to the greater proportion of cactus pear in the mixed silages. Sá et al. (2020) reported effluent losses of 12 kg ton⁻¹, attributing this to the mucilage content of cactus pear. A similar pattern was observed in the present study: despite fermentation, the silages retained high moisture content (i.e., low dry matter), due to the substantial water-holding capacity provided by cactus pear mucilage. This mucilage, composed of polysaccharides acting as absorbent, water-retaining gels, minimizes effluent drainage. Its main polysaccharides include galacturonic acid, arabinose, galactose, rhamnose, and xylose (McGarvie & Parolis, 1979; Trachten & Mayer, 1981; Habibi et al., 2004). The effluent losses observed in this study were similar to those reported by Santos et al. (2020). Pereira et al. (2019) demonstrated that incorporating legumes into mixed silages reduces effluent losses, which was also evident in the present study: legume inclusion levels of 17% and 35% in silages (4) and (5) significantly reduced effluent production ($P < 0.01$). Likewise, the inclusion of millet (20% of DM) contributed to reduced effluent losses in silage (2).

The lower dry matter recovery observed in silages (3) and (8) was associated with their final pH values (4.77 and 4.76, respectively), which remained above 4.5. This indicates a prolonged fermentation process within the silo, leading to reduced dry matter recovery (Santos et al., 2020). With the exception of silages (3) and (8), the mixed silages exhibited high dry matter recovery, in some cases exceeding 90%, indicating minimal fermentative losses.

Cactus pear contains high concentrations of minerals, especially potassium and calcium (Sá et al., 2021; Barros et al., 2025), which exceed the mineral content of gliricidia (Brito et al., 2020; Sá et al., 2021). Thus, the increased proportion of cactus pear (Table 1) originating from systems managed with mineral fertilization resulted in higher ash concentrations in silages (1), (2), and (3). Mineral fertilization also enhanced TDN and reduced NDF in silage (4) compared to silage (5).

According to Brito et al. (2020), cactus pear contains lower ether extract (EE) than gliricidia, which explains the lower EE concentrations ($P < 0.01$) in silages (1) and (2), in contrast to silages (4), (5), (6), and (8), all of which included gliricidia in their composition.

Silage (2) exhibited the lowest crude protein content (5.15%; Table 4), differing ($P<0.05$) from the other silages. This results from the low CP concentration (5.30%) of the forage produced under the integrated cactus pear-millet system with organic fertilization (Table 2). In contrast, silages (4), (5), and (7) did not differ from each other but had higher CP concentrations than the other silages, due to the greater contribution of gliricidia.

The morphological composition of the forages derived from the integrated systems included approximately 17%, 29%, and 35% gliricidia, contributing to the increased ADF concentrations in silages (4), (5), and (8), respectively. As reported by Brito et al. (2020), the ADF concentration of gliricidia is approximately 33% of DM, whereas cactus pear contains much lower ADF levels ($\approx 14\%$).

Silages (1) and (3), which had the lowest dry matter contents, exhibited a mucilaginous, semi-liquid, and amorphous consistency, requiring containers for proper handling. In contrast, silages (5) and (8) displayed a solid consistency, whereas the remaining silages showed a pasty texture. The formation of mucilage immediately after chopping the cactus cladodes occurs due to the rupture of chlorenchyma and parenchyma cells, exposing hydrocolloid gels that confer high water-retention capacity. This characteristic helps reduce effluent production and increases dry matter content in the silages (Jesus et al., 2022). It is noteworthy that the dry matter levels observed in this study were considerably lower than those recommended in the literature for producing well-preserved silages, which range from 28% to 40% DM (McDonald et al., 1991).

Silages (3) and (8) presented pH values of 4.76 and 4.77, respectively, and differed significantly ($P<0.01$) from the other mixed silages (Table 4). These values exceeded the ideal pH range, indicating a prolonged fermentation process, greater losses, and reduced dry matter recovery (Table 3). Silages produced from non-conventional forage species, which are typically wetter and possess a higher buffering capacity, tend to stabilize within a broader pH range, between 3.7 and 4.5 (Pereira et al., 2019; Brito et al., 2020; Sá et al., 2021; Jesus et al., 2022). Conversely, silages (1), (2), (4), (5), (6), (7), and (9) exhibited pH values within the ideal range, indicating adequate preservation and efficient fermentation with reduced losses (McDonald et al., 1991).

On average, the forages produced in the integrated systems contained 2.13% and 16.72% soluble carbohydrates on as fed and dry matter basis, respectively (Table 2), prior to ensiling. Cactus pear is known to contain high levels of soluble carbohydrates, typically ranging from 6% to 16%, with values near 15% being common (Brito et al., 2020). Soluble carbohydrates are essential substrates for lactic fermentation, which is the desirable pathway during ensiling (Brito et al., 2020). However, high levels of residual soluble carbohydrates remaining in the silage after fermentation (Table 3) are undesirable. These compounds serve as readily degradable substrates for filamentous fungi, yeasts, and other opportunistic microorganisms, accelerating silage deterioration after silo opening. Their rapid metabolism contributes to aerobic instability, marked by increased temperature and reduced preservation quality.

Silage (3) exhibited a greater buffering capacity than silage (1), and both differed from the remaining silages (Table 4). Buffering capacity, defined as the resistance of ensiled mass to pH change, varies among forage species and is higher in gliricidia, followed by cactus forage (Brito et al., 2020), and lower in millet (Silva et al., 2020). This variation is associated with intrinsic plant characteristics, such as dry matter content, nitrogen concentration, mineral composition, soluble carbohydrates, and organic acids. Therefore, silages (1) and (3) presented greater buffering capacity due to their lower concentrations of lactic acid, the primary strong acid responsible for reducing pH during fermentation.

Ammonia nitrogen (N-NH₃) levels ranged from 3.18% to 4.66% of total nitrogen, with no significant differences among the mixed silages. These values fall within the recommended limits for high-quality silages, typically below 10% of total nitrogen (Brito et al., 2020), indicating that protein degradation by undesirable microorganisms was minimal.

The presence of yeasts was detected in silages (1), (2), (7), (8), and (9). These microorganisms are undesirable because they consume soluble carbohydrates and produce CO₂, resulting in ethanol formation and dry matter losses (Muck et al., 2018). Lactic acid bacteria (LAB) are responsible for lactic acid production and pH reduction, whereas molds and yeasts may reduce silage intake and energy value, negatively affecting dry matter recovery. Additionally, they increase silage pH and accelerate aerobic deterioration. High populations of enterobacteria can also reduce silage quality

by producing toxic compounds and delaying the necessary pH decline for proper preservation.

The populations of lactic acid bacteria (LAB), molds, and yeasts varied among treatments, as the epiphytic microbiota of forages derived from integrated forage-production systems is a determining factor in the intensity and nature of silage fermentation. This variability is especially influenced by mineral or organic fertilization practices, which can alter the physiological and productive characteristics of the forage crops.

Silages (4), (5), (6), (7), and (9) exhibited adequate concentrations of organic acids, indicating the absence of enterobacterial activity and no evidence of *Clostridium* fermentation. Instead, these silages underwent a desirable fermentation pattern initially dominated by heterofermentative LAB and later by homofermentative LAB (Pereira et al., 2019; Sá et al., 2021). These silages also showed final pH values within the ideal range (3.74 to 3.97), confirming proper preservation.

In silage (8), heterofermentative lactic fermentation likely occurred, as suggested by similar concentrations of lactic acid (35.74 g kg⁻¹ DM) and acetic acid (36.33 g kg⁻¹ DM). The final pH of 4.77, however, was outside the ideal range for well-preserved silages produced from non-conventional forage plants, which should fall between 3.7 and 4.5 (Pereira et al., 2019; Brito et al., 2020; Sá et al., 2021; Jesus et al., 2022).

Silage (2) contained lower butyric acid levels (39.88 g kg⁻¹ DM) than silages (1) and (3), and also differed from the remaining mixed silages. In silage (2), initial butyric fermentation was followed by heterofermentative lactic fermentation, supported by the availability of residual soluble carbohydrates. This process resulted in lactic acid production of 74.37 g kg⁻¹ DM and an intermediate final pH of 4.29. Conversely, in silages (1) and (3) (Table 4), excessively high moisture favored the proliferation of *Clostridium*, which produced butyric acid (Muck, 2010) at levels exceeding those recommended by McDonald et al. (1991). According to these authors, butyric acid concentrations above 10 g kg⁻¹ DM indicate undesirable fermentation, compromising silage quality. *Clostridium* spp., which are strict anaerobes, metabolize carbohydrates, proteins, and lactic acid to produce butyric acid, characterized by a strong and unpleasant odor (Muck, 2010). Silage is considered poor when butyric acid levels range from 30 to 50 g kg⁻¹ DM (McDonald et al., 1991), and even concentrations above

2% (20 g kg⁻¹ DM) can reduce dry matter intake due to odor (Senel & Owed, 1967; Jonsson, 1991).

Higher acetic acid concentrations in silages (1) and (3) may be associated with heterolactic fermentation, producing both lactic and acetic acids. *Propionibacterium* spp. (Kung et al., 2018), also heterofermentative, can produce acetic and propionic acids in the ensiled mass. This pattern indicates limited activity of homofermentative LAB in these silages (Pereira et al., 2020; Sá et al., 2020).

The elevated propionic acid content observed in silage (1) may be attributed to *Clostridium propionicum*, which converts excess butyric acid into propionic acid (Kung et al., 2018).

The short aerobic stability observed across silages was likely due to their high moisture content and the presence of residual soluble carbohydrates (3.69% to 8.91% DM; Table 4). Upon silo opening, these carbohydrates become immediately available to spoilage microorganisms, accelerating nutrient losses and reducing aerobic stability, effects intensified in silages with low dry matter, as seen in this study. Exposure to air promotes the growth of filamentous fungi and yeasts, leading to undesirable secondary fermentations. Although acetic acid is typically associated with improved aerobic stability in drier silages, this effect was not observed here due to the high moisture content.

Aerobic spoilage microorganisms, particularly filamentous fungi and yeasts, rapidly consume soluble carbohydrates, causing a rapid temperature rise and triggering aerobic deterioration. These microorganisms proliferate in the presence of oxygen, generating heat, releasing water, consuming lactic acid, and increasing silage pH, ultimately reducing the nutritional value of the feed (Muck et al., 2018). Thus, the observed aerobic stability of only 3 hours represents a significant disadvantage.

Yeasts are major contributors to silage deterioration, particularly after aerobic exposure. They cause substantial dry matter losses and can grow at pH values below 3.8. Under anaerobic conditions, they can also metabolize lactic acid, reducing its concentration and increasing silage pH, which favors undesirable fermentations (Muck, 2010; Muck et al., 2018).

CONCLUSION

Integrated systems combining cactus pear with gliricidia and managed with organic fertilization (CP+G+OF), mineral fertilization (CP+G+MF), or both organic and

mineral fertilization (CP+G+MF+OF), as well as integrated systems cultivated with cactus pear, millet, and gliricidia and subjected to mineral (CP+M+G+MF) or combined mineral/organic fertilization (CP+M+G+MF+OF), produce forages that, when ensiled, exhibit superior fermentative quality, appropriate levels of organic acids, and greater dry matter recovery.

Harvesting the forage in integrated forage production systems without leaving residual biomass results in higher moisture in the ensiled material. This is primarily due to the substantial contribution of forage cactus and to the variability in forage production associated with organic and/or mineral fertilization strategies.

Silages originating from these integrated forage production systems are excessively moist and display aerobic stability lasting only about 3 hours. Therefore, the inclusion of large proportions of cactus pear in mixed silages requires further evaluation.

It is important to emphasize that the producer can employ some strategies to reduce the proportion of cactus pear from the integrated system to be ensiled, such as: 1) harvesting the cactus pear while preserving the secondary cladodes; 2) cactus pear has a flexible harvest interval, allowing millet and gliricidia to be harvested 90 days after regrowth without compromising the chemical composition of the Cactaceae; 3) anticipating the harvest of millet and gliricidia by a few hours, allowing pre-drying of these forage plants; 4) harvesting cactus pear annually also reduces its proportion compared to biennial harvesting.

In just three hours after opening, the mixed silage begins the deterioration process. To minimize this problem of short-term aerobic stability breakdown, silage can be provided in the trough more than once a day for the animal, providing smaller quantities.

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