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Quality of Forage Cactus Silage with the Addition of Hay from Forages Adapted to the Semiarid Region

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ABSTRACT

This study investigated the effects of including hays from different forages adapted to the semiarid region on the forage cactus (*Opuntia ficus-indica* (L.) Mill) silage quality. A completely randomized design, with five treatments was used: pure forage cactus and forage cactus associated with 30% hay from gliricidia (*Gliricidia sepium*), pornunça (*Manihot* spp.), pigeon pea (*Cajanus cajan*), and silk flower (*Calotropis procera*). Adding hays reduced gas and effluent losses ($p < 0.01$), improved dry matter (DM) recovery (around 97% vs. 63% in pure forage cactus; $p < 0.01$), and reduced the pH (4.26–4.68 vs. 5.30; $p < 0.01$). The chemical composition improved, with higher DM ($p < 0.01$), crude protein ($p < 0.01$), and total digestible nutrients ($p = 0.02$) contents. The *in situ* degradability of DM varied by hay type: Silk flower showed the highest potential and effective degradability at all passage rates, while pigeon pea had the lowest. The inclusion of hays adapted to the semiarid region enhanced the fermentative stability, nutritional value, and digestibility of forage cactus silage. Among the tested additives, silk flower and gliricidia were the most effective in improving silage quality and preservation.

1 | Introduction

Forage cactus (*Opuntia ficus-indica* (L.) Mill) is a strategic feed resource for ruminants in arid and semiarid regions due to its high drought tolerance, high biomass productivity, and significant nonstructural carbohydrate content (Nascimento et al. 2024). Nevertheless, these chemical characteristics confer high fermentability, favoring the multiplication of pathogenic microorganisms when the cladodes are fed fresh (Oliveira et al. 2025). Studies link episodes of diarrhea in ruminants to cactus contamination by enterobacteria, highlighting risks to animal health and feed safety (Paulino et al. 2021; Vieira et al. 2022).

Management strategies, such as the inclusion of ingredients with lower soluble carbohydrate and higher physically effective fiber content, are effective measures to mitigate these risks. Another complementary alternative is ensiling, in which controlled lactic acid fermentation promotes rapid acidification in an anaerobic environment, inhibiting *Enterobacteriaceae* and reducing losses associated with excess moisture (Brito et al. 2020). It is important to note that despite the low dry matter (DM) content of raw forage cactus, after grinding the cladodes for ensiling, mucilage is released, which envelops the cellular fluids and mitigates effluent losses (Dall-Orsoletta et al. 2017).

Still, to maximize the benefits of the ensiling process and improve the nutritional profile of the roughage, the use of hay from leguminous forages adapted to the semiarid region is a particularly effective strategy (Borges et al. 2025). Due to the haymaking process, these forages have high DM contents and, as legumes, are also notable for their high crude protein (CP) content (Sá et al. 2024). These attributes increase the DM content of the mass to be ensiled, and the energy and protein density of the mixture, which favors mass compaction and contributes to better DM recovery (DMR).

Species such as gliricidia (*Gliricidia sepium*), pornunça (*Manihot* spp.), pigeon pea (Guandu or feijão guandu - *Cajanus cajan*), and silk flower (*Calotropis procera*) are usually available in the semiarid region and combine these characteristics, permitting the creation of cactus silages with better nutritional balance and superior microbiological safety (Oliveira et al. 2025). Despite this potential, the literature still lacks comparative studies that systematically assess the effects of cactus ensilage combined with these different hay species.

In this context, the present study aimed to evaluate the effects of the inclusion of hays from different forages adapted to the semiarid region on fermentation losses, fermentation profile, chemical composition, and *in situ* degradability of DM of forage cactus silage. Hence, it was tested the hypothesis that the addition of these hays simultaneously improves the fermentation characteristics and nutritional value of the ensiled material.

2 | Materials and Methods

2.1 | Experiment Location and Experimental Design

The experiment was conducted at the São Gonçalo dos Campos Experimental Farm, affiliated with the School of Veterinary Medicine and Animal Science of the Federal University of Bahia, in São Gonçalo dos Campos, BA, Brazil. Fifteen mini-silos made of polyvinyl chloride tubes (10 cm in diameter × 40 cm in length) were equipped with lids fitted with Bunsen valves to allow the release of gases produced during fermentation.

The experimental design was completely randomized, with five treatments and three replicates. The treatments consisted of pure forage cactus silage (100% forage cactus cactus), forage cactus silage with gliricidia hay (70% forage cactus + 30% gliricidia on natural matter (NM) basis), forage cactus silage with pornunça hay (70% forage cactus + 30% NM pornunça), forage cactus silage with pigeon pea hay (70% forage cactus + 30% NM pigeon pea), and forage cactus silage with silk flower hay (70% forage cactus + 30% NM silk flower).

2.2 | Nutritional Value of Forages and Ensiling Process

The forage cactus used for ensiling was the nopal cactus (*Opuntia ficus-indica* (L.) Mill) cv. Giant or Giant Cactus. The cactus was harvested at the ages over 18 months. The giant cactus harvest was carried out in the early hours of the day, using all the cladodes of the plant, keeping only the primary cladode in the field. To make hay from gliricidia, pornunça, pigeon pea, and silk flower, young (leafy) branches measuring approximately 1 cm in diameter were harvested. These branches were processed in a stationary forage machine and dehydrated in the sun. The chemical composition of the forage cactus and hay used in silage production is presented in Table 1.

The forage cactus cladodes were ground in a stationary disintegrator, obtaining cubes of approximately 2 cm. The forage cactus and hay were weighed separately, respecting the proportion of 70% forage cactus and 30% hay and then homogenized in a suitable container. The mixture was stored in mini-silos, compacted until reaching a density of approximately 700 kg/m^3.

A 1.5 kg layer of sand was added to the bottom of each silo, separated from the forage by a polyethylene screen to prevent contamination of the ensiled material. All silos were weighed before ensiling (tube + lid + sand + screen) and after filling and sealing, allowing for the estimation of gas losses and DMR. The silos were closed and stored indoors at room temperature for 60 days. Before opening, the mini-silos were weighed again when closed, and after opening, they were weighed without the silage.

2.3 | Fermentation Losses and Fermentative Profile

Mass losses due to gases during ensiling (kg) was determined by the difference between the mass of the silos immediately after closing and before opening. Relative mass loss was obtained by dividing this value by the initial mass of the ensiled forage,

TABLE 1 | Chemical composition of forage cactus and forage hay used in silage production.

Item (g Kg^{-1} DM)	Forage cactus	Gliricidia	Pornunça	Pigeon pea	Silk flower
Dry matter (%)	4.2	88.6	89.6	90.1	94.3
Mineral matter	130.9	74.9	96.0	89.4	162.0
Crude protein	49.7	159.0	119.1	93.1	111.8
Ether extract	18.4	26.5	53.3	40.0	54.8
Neutral detergent fiber	407.0	508.1	415.6	508.8	355.6
Acid detergent fiber	295.5	244.0	248.3	319.6	226.0
Hemicellulose	111.5	264.1	167.3	189.2	129.6
Cellulose	190.9	111.4	143.8	196.4	140.7
Lignin	104.6	132.6	104.5	122.9	85.3
Total carbohydrates	801.0	739.8	731.6	777.5	671.4
Nonfibrous carbohydrates	394.0	231.7	316.0	268.7	315.8
Total digestible nutrients	578.3	607.4	604.9	564.8	617.5

discounting the silo tare weight, according to the methodology described by Jobim et al. (2007).

Effluent losses were estimated by the amount of liquid retained in the sand placed at the bottom of the silos, following the procedure reported by Zanine et al. (2010). DMR was calculated as the percentage of DM remaining at the time of opening relative to the initial amount, according to the equation proposed by Jobim et al. (2007).

The pH of the samples was determined using a portable digital pH meter, according to the methodology described by Bolsen et al. (1992). Buffering capacity (BC) analysis was performed according to Playne and McDonald (1966) and expressed as the milligram equivalent of alkali required to raise the pH from 4.0 to 6.0 per 100 g of DM.

2.4 | Chemical Composition

Forage cactus and hay samples collected before ensiling, as well as silage samples after opening the silos, were placed in labeled plastic bags and stored at −20°C until laboratory analysis. Prior to analysis, the samples were thawed at room temperature and dried in a forced-air oven at 55°C for 72 h. Subsequently, they were ground in Willey-type knife mills with 1 and 2 mm sieves.

The DM (DM; method 934.01), mineral matter (MM) (MM; method 930.06), ether extract (EE; method 920.39), and CP (CP; method 981.10) contents of the predried samples were determined, as described by the AOAC (1990). Neutral detergent fiber (NDF) and acid detergent fiber (ADF) analyses followed the methodology proposed by Van Soest et al. (1991). The total digestible nutrients (TDNs) were estimated according to the equation described by Cappelle et al. (2001).

Lignin content was determined by the Klason method, using 72% sulfuric acid, according to Theander and Westerlund (1986). The total carbohydrate (tCHO) and nonfibrous carbohydrate (NFC) fractions were calculated according to models proposed by Sniffen et al. (1992).

2.5 | *In Situ* Degradability of Dry Matter

For the *in situ* degradability trial, the samples were ground through a 2-mm sieve and packaged in nonwoven synthetic fiber bags (NWT 100 g m^{-2}), measuring 5 × 5 cm, containing approximately 0.5 g of DM per bag, as proposed by Nocek (1988).

Incubation was performed in duplicate using two castrated male crossbred cattle (Holstein × Zebu), with an average age of 23 months and an average body weight of 340 kg. The animals were rumen-cannulated following a protocol approved by the Animal Use Ethics Committee of the School of Veterinary Medicine and Animal Science at UFBA (CEUA/UFBA: permit number - 026/2021) and kept grazing exclusively on pangola grass (*Digitaria decumbens*), with free access to water.

The bags were randomly distributed and incubated simultaneously in the rumen and removed according to incubation periods of 0, 6, 12, 24, 48, 72, 96, and 120 h. Zero time corresponded to washing the bags in cold running water to determine the soluble fraction. After removal, the bags were washed in running water until the water was clear, and no adhered particles were present. They were then dried in a forced-air oven at 60°C for 72 h and weighed, following the methodologies recommended by the AOAC (1990). *In situ* DM degradability was calculated by the difference between the initial weight and the residual weight after incubation, expressed as a percentage (%).

The sum of the fractions “a” and “b” was adopted as potential degradability (PD). Effective DM degradability was estimated considering passage rates of 2, 5, and 8% h^{-1}, corresponding to low, medium, and high dietary intake levels, respectively, as recommended by the AFRC (1993), using the equation proposed by Ørskov and McDonald (1979).

2.6 | Statistical Analysis

The data on losses, fermentation profile, and chemical composition were subjected to analysis of variance, and means were compared using Tukey's test at 5% probability using the SAS procedure (version 9.4; SAS Institute Inc., Cary, NC).

The *in situ* degradability data were analyzed using mixed models (PROC MIXED, SAS Institute Inc., Cary, NC, USA). The experimental treatments and incubation times were considered as fixed effects, as well as their interaction. The fistulated animals were included in the model as a random effect. Incubation time was treated as a repeated measure, and the covariance structure was selected based on the Akaike Information Criterion. The nonlinear coefficients a, b, and c, resulting from the degradability test, were estimated using interactive Gauss–Newton procedures, and the means were compared using confidence intervals at 95%.

3 | Results

3.1 | Fermentation Losses and Fermentative Profile

The inclusion of hay significantly reduced gas and effluent losses compared to pure forage cactus silage ($p < 0.05$) (Table 2). While pure forage cactus silage presented the highest losses (GL = 19.06 kg Mg^{-1}; EL = 178.76 kg Mg^{-1}), silages with hay presented values close to zero for GL (0.21–0.42 kg Mg^{-1}) ($p < 0.01$), and approximately ten times lower for EL (17.80–22.15 kg Mg^{-1}) ($p < 0.01$). DMR was higher in silages with hay (97.4–97.7%), in contrast to 63.1% for pure forage cactus silage ($p < 0.01$).

The pH was also reduced with the addition of hay (4.26–4.68 vs. 5.30 in pure forage cactus) ($p < 0.05$). The buffer capacity varied according to the forage, with the highest value observed for silk flower (50.82 mEq 100 g DM^{-1}) and the lowest for pure cactus silage (29.08 mEq 100 g DM^{-1}) ($p = 0.05$).

3.2 | Chemical Composition

The addition of hay caused significant differences in the chemical composition of the forage cactus silages (Table 3). DM content was significantly influenced ($p < 0.01$), rising from only 11.42% in pure cactus to values between 27.40% and 33.51% in silages with hay, with emphasis on pornunça, which had the highest value (33.51%). The MM also changed ($p < 0.01$), being higher in pure cactus (233.6 g kg^{-1} DM) and lower in silages containing hay, with values ranging from 94.8 g kg^{-1} DM in pigeon pea to 172.9 g kg^{-1} DM in silk flower. There was a significant increase in CP contents ($p < 0.01$), as pure forage cactus had the lowest value (75.3 g kg^{-1} DM), while gliricidia resulted in the highest

TABLE 2 | Fermentative losses and fermentation profile in forage cactus silages with forage hay adapted to the semiarid region.

Item	Forage cactus silage					SEM	*p*-value
	Pure	Gliricidia	Pornunça	Pigeon pea	Silk flower		
Gas losses	19.06_a	0.42_b	0.21_c	0.33_{bc}	0.38_{bc}	2.13	<0.01
Effluent losses	178.76_a	21.75_b	22.15_b	17.80_c	21.73_b	16.89	<0.01
DMR	63.06_b	97.41_a	97.57_a	97.74_a	97.45_a	3.69	<0.01
pH	5.30_a	4.68_b	4.26_d	4.48_c	4.34_{cd}	0.10	<0.01
Buffer capacity	29.08_c	39.68_b	36.55_b	41.97_b	50.82_a	2.06	0.05

Note: Means in a row followed by the same letter do not differ from each other, according to Tukey's test at 5% probability; SEM = standard error of the mean; Gas losses, expressed in Kg^{-1} DM; effluent losses, expressed in Kg^{-1} DM, DMR = dry matter recovery (expressed in %); buffer capacity, expressed in mEq 100 g^{-1} DM.

TABLE 3 | Chemical composition of pure forage cactus silages and forage cactus silages mixed with gliricidia, pornunça, pigeon pea, and silk flower hay.

Item (g Kg^{-1} DM)	Forage cactus silage					SEM	*p*-value
	Pure	Gliricidia	Pornunça	Pigeon pea	Silk flower		
Dry matter (%)	11.42_d	27.40_c	33.51_a	31.22_b	30.59_b	2.05	<0.01
Mineral matter	233.6_a	105.7_{bc}	112.2_b	94.8_c	172.9_b	13.6	<0.01
Crude protein	75.3_d	209.0_a	153.9_b	127.2_c	147.8_b	11.2	<0.01
Ether extract	23.4	24.2	47.6	37.2	58.2	3.70	0.06
NDF	478.6	469.8	417.1	457.5	301.5	17.2	0.06
ADF	308.9_a	261.1_{bc}	250.6_c	291.7_{ab}	207.9_d	9.43	0.02
Hemicellulose	169.7_b	208.7_a	166.6_b	165.8_b	93.7_c	9.95	0.05
Cellulose	219.2	123.0	138.6	183.6	130.3	9.90	0.06
Lignin	89.7	138.1	112.2	108.1	77.6	6.03	0.06
Total carbohydrates	667.7_b	661.1_b	686.3_b	740.8_a	621.2_c	10.3	0.02
NFC	189.1	191.3	269.1	283.3	319.7	14.1	0.08
TDN	570.8_c	597.7_{ab}	603.7_a	580.5_{bc}	627.7_a	5.30	0.02

Note: Means in the line followed by different letters differ from each other by Tukey's test at 5% probability.
Abbrevations: ADF = acid detergent fiber, NDF = neutral detergent fiber, NFC = nonfibrous carbohydrates, SEM = standard error of the mean, TDN = total digestible nutrients.

(209.0 g kg^{-1} DM), followed by pornunça (153.9 g kg^{-1} DM) and silk flower (147.8 g kg^{-1} DM), with the lowest value observed for pigeon pea (127.7 g kg^{-1} DM).

The ADF content was reduced by the addition of hay ($p = 0.02$), ranging from 308.9 g kg^{-1} DM in pure forage cactus to 207.9 g kg^{-1} DM in silage with silk flower. Likewise, hemicellulose showed a significant effect ($p = 0.05$), being higher in gliricidia (208.7 g kg^{-1} DM) and reduced in silk flower (93.7 g kg^{-1} DM). In tCHO, a difference was observed between treatments ($p = 0.02$), with the highest value in silage containing pigeon pea (740.8 g kg^{-1} DM) and the lowest in silage with silk flower (621.2 g kg^{-1} DM). Finally, TDN showed a significant variation ($p = 0.02$), being lower in pure forage cactus (570.8 g kg^{-1} DM) and higher in silk flower (627.7 g kg^{-1} DM) and pornunça (603.7 g kg^{-1} DM).

3.3 | *In Situ* Dry Matter Degradability

The DM PD varied among the silages (Table 4). The highest PD was observed in the silage with silk flower hay (61.92%), while the lowest was observed in the silage with pigeon pea (33.08%). Pure forage cactus presented an intermediate value (53.81%).

The effective degradability (ED), calculated for passage rates of 2, 5, and 8% h^{-1}, showed differences among the treatments. Silk flower presented the highest ED values at all rates (55.21%, 49.43%, and 45.99%, respectively), while pigeon pea maintained the lowest (29.52%, 26.22%, and 24.15%). Pure forage cactus exhibited values of 37.96%, 30.56%, and 27.48%, respectively, for the three passage rates. In the analysis of ruminal degradation parameters (Table 5), the soluble fraction (a) varied between treatments, being higher in silage with silk flower (32.49%) and gliricidia (27.85%), while pigeon pea had the lowest value (15.07%).

The potentially degradable fraction (b) was higher in pure forage cactus (33.77%) and silk flower (29.42%), contrasting with the lower values obtained in silages with gliricidia (18.59%) and pornunça (16.58%). The degradation rate of the insoluble fraction (c) was also influenced by the addition of hay, with gliricidia (0.36 h^{-1}) and pornunça (0.32 h^{-1}) having the highest rates, while silk flower (0.07 h^{-1}) and pigeon pea (0.08 h^{-1}) had the lowest.

The *in situ* DM degradation curve (Figure 1) confirmed these results. Silage containing silk flower showed the highest DM degradation rates over the incubation period, followed by gliricidia

TABLE 4 | PD and ED of DM of forage cactus silages with hay from forages adapted to the semiarid region, calculated for ruminal passage rates of 2, 5, and 8% per hour.

Forage cactus silages	PD	ED as a function of the hourly passage rate		
		0.02	0.05	0.08
Pure	53.81	37.96	30.56	27.48
Gliricidia hay	46.45	45.46	44.16	43.04
Pornunça hay	40.99	40.01	38.74	37.66
Pigeon pea hay	33.08	29.52	26.22	24.15
Silk flower hay	61.92	55.21	49.43	45.99

Note: PD = (a + b); ED = a + [(b.c)/(c + k)]

TABLE 5 | Parameters of ruminal degradation of DM of forage cactus silages supplemented with 30% hay from forages adapted to the semiarid region.

Parameter	Estimative	95% Confidence Interval		SEM	*p*-value
		Lower limit	Upper limit		
Pure forage cactus silage					
a (%)	20.05	13.47	26.63	3.16	<0.01
b (%)	33.77	22.58	44.95	5.38	
c (/h)	0.02	0.89	0.05	0.01	
Forage cactus silage with gliricidia hay					
a (%)	27.85	21.28	34.42	3.16	<0.01
b (%)	18.59	11.47	25.72	3.43	
c (/h)	0.36	0.18	0.90	0.26	
Forage cactus silage with pornunça hay					
a (%)	24.41	17.51	31.31	3.32	0.06
b (%)	16.58	9.09	24.07	3.60	
c (/h)	0.32	0.18	0.82	0.32	
Forage cactus silage with Pigeon pea hay					
a (%)	15.07	11.82	18.32	1.56	<0.01
b (%)	18.01	14.44	21.57	1.71	
c (/h)	0.08	0.02	0.04	0.12	
Forage cactus silage with silk flower hay					
a (%)	32.49	24.94	40.04	3.63	<0.01
b (%)	29.42	21.13	37.72	3.99	
c (/h)	0.07	0.02	0.11	0.02	

Note: a: soluble fraction; b: potentially degradable fraction; c: constant rate of DM degradation; SEM: standard error of the mean.

and pornunça, while pure forage cactus and pigeon pea had the lowest DM disappearance rates.

4 | Discussion

4.1 | Fermentation Losses and Fermentative Profile

Forage cactus silage showed contrasting performance when used alone or associated with legume and dicotyledon hay adapted to the semiarid region. Forage cactus silage showed higher losses due to gases (19.06 kg Mg^{-1}) and effluents (178.76 kg Mg^{-1}), as well as lower DMR (63.06%). This behavior is directly related to its low DM content of forage cactus (4.2%), which compromises lactic fermentation and favors undesirable secondary fermentations (Santos et al. 2024). Excess moisture dilutes the acids produced in the fermentation process, making it difficult to quickly reduce pH and, consequently, increasing silage's vulnerability to losses (Liu et al. 2025).

It should be noted that, despite the formation of mucilage after crushing forage cactus cladodes, whose emulsifying effect is capable of involving fluid compounds and reducing losses (Dall-Orsoletta et al. 2017), this characteristic was not enough to prevent nutrient leaching. Thus, mucilage, although partially

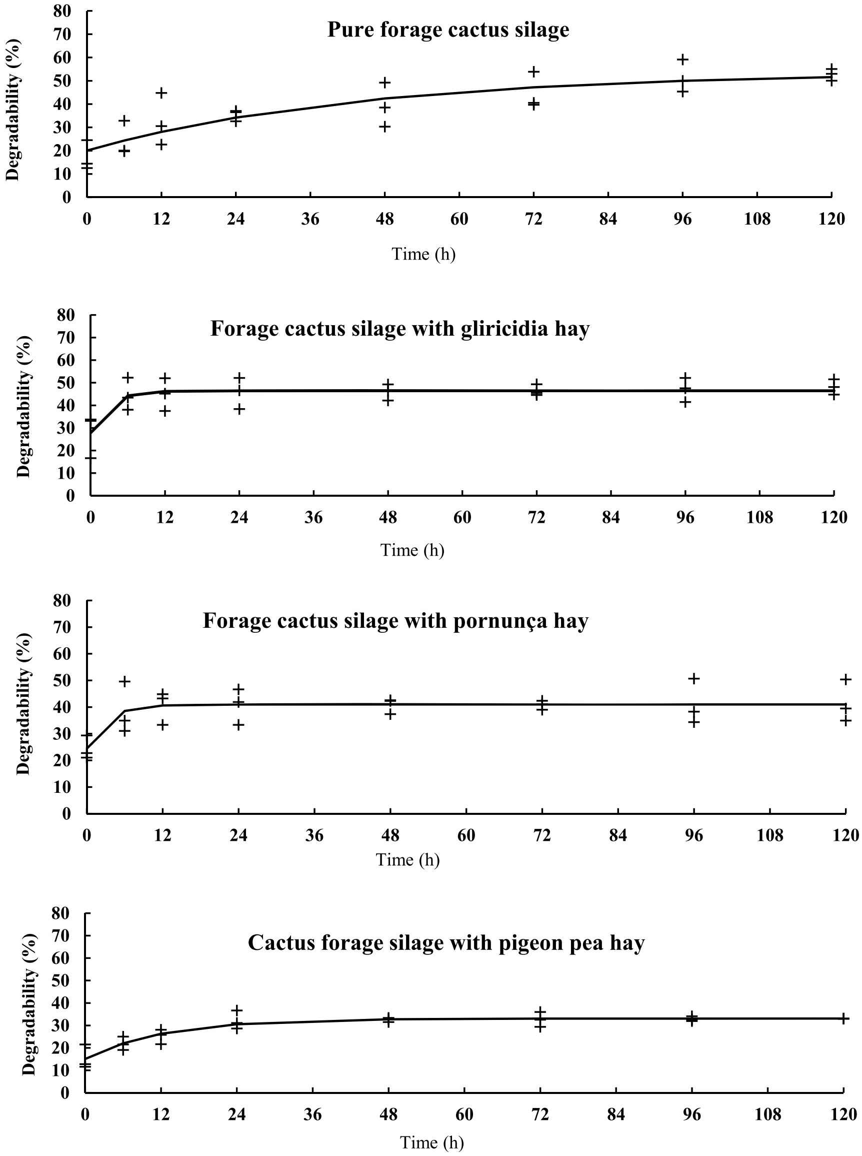

FIGURE 1 | Percentage of *in situ* DM degradation of forage cactus silages with gliricidia, pornunça, pigeon pea, and silk flower as a function of incubation times of up to 120 h.

contributing to retention, does not compensate for the excess moisture of the forage when the forage cactus is ensiled in isolation, without the addition of dry roughage.

In contrast, the addition of hays drastically reduced such losses, since dry roughage acts on the absorption of excess water, minimizes nutrient leaching, and provides conditions more suitable for the predominance of lactic fermentation, resulting in more stable and better-quality silages. In the present study, among the hays tested, pigeon pea hay showed the lowest loss per effluent (17.8 kg Mg^{-1}), an effect related to its high DM content and the higher proportion of NDF, which contribute to retain moisture. Pornunça, on the other hand, stood out for its lower gas losses (0.21 kg Mg^{-1}), the result of a more balanced fermentation profile, possibly influenced by the presence of bioactive compounds capable of modulating microbial activity and restricting undesirable secondary fermentations (Schultze-Kraft et al. 2018; Quintero-Anzueta et al. 2021).

These results reinforce the evidence that combining tropical legumes with other roughage improves the conservation of wet forages (Paul et al. 2020). Furthermore, the high DMR (>97%) obtained with hay confirms the efficiency of this strategy, which is especially important in semiarid regions, where the supply of forage is seasonal and limited.

In addition, the improvement in fermentation capacity, with a probable increase in lactic acid production, resulted in lower pH values in silages with hay compared to isolated forage cactus. It should be noted that, although hays have a greater BC due to their content of proteins, minerals (i.e., calcium, potassium, and magnesium), phenolic compounds, and organic acids, recognized for exerting this effect (McDonald et al. 2020; Rodrigues et al. 2023), the final pH was lower than that observed in pure forage cactus, reaching up to 4.26 in pornunça, against 5.3 in isolated forage cactus.

Although the present results showed BC values ranging from 29.08 to 50.82 mEq 100 g^{-1} DM, these values are consistent with those reported by Kung Jr. et al. (2018). According to these authors, the BC of corn silage ranges from 20 to 25 mEq 100 g^{-1} DM, whereas legumes present values between 50 and

55 mEq 100 g^{-1} DM. Therefore, the BC values observed in the present study are in agreement with those reported in the literature, indicating that the inclusion of hays with higher protein content does not negatively affect the silage fermentation process or the reduction in pH.

This result shows that the inclusion of hay, in addition to correcting excess moisture, favored the action of lactic acid bacteria and the rapid accumulation of organic acids, promoting a more efficient fermentation environment and ensuring greater stability of the ensiled mass.

4.2 | Chemical Composition

Among the silages evaluated, pure forage cactus had the lowest DM content (11.42%), reflecting the low DM content in the *in natura* cladodes (4.2%), a characteristic of the succulent physiology of this species (Fradera-Soler et al. 2022). The inclusion of hay corrected this limitation, raising the DM of the silages to values between 27.40% (gliricidia) and 33.51% (pornunça). This increase is related to the high DM content of the hays used in this study (>880 g Kg^{-1} of NM), which contributed to the absorption of forage cactus moisture.

Despite the variations between species, the final DM values of the mixed silages remained close to 30%, a range considered adequate for the silo conservation process (McDonald et al. 1991).

Regarding the MM content, pure forage cactus silage had the highest concentration (233.6 g kg^{-1} DM) compared to the others, which is explained by the characteristics of the *in natura* forage cactus plant. As a cactus with crassulaceous acid metabolism, forage cactus accumulates mineral salts in cladodes, especially potassium, calcium, and magnesium (Dubeux Júnior et al. 2021) as a strategy for osmotic adjustment and maintenance of juiciness, reflected in the values observed after ensiling (Ogburn and Edwards 2010).

The lower CP content in pure forage cactus silage (75.3 g kg^{-1} DM) is due to the characteristic composition of forage cactus, which has low protein content, being more valued for the water and energy it provides, which requires protein supplementation in the diet. Among the hays, forage cactus silage with gliricidia stood out with the highest CP content (209.0 g kg^{-1} DM), which is in line with the high protein content of the leaves of this forage legume (≈159 g kg^{-1} DM in the ingredient). This high value is explained by its condition as an arboreal legume that fixes atmospheric nitrogen, through the symbiotic association with rhizobia, which results in greater accumulation of nitrogenous compounds, especially in leaves and young branches (Kaba et al. 2019).

On the other hand, pigeon pea had the lowest CP content among the hay silages (127.2 g kg^{-1} DM), a result compatible with the value observed in the ingredient (≈93 g kg^{-1} DM in the ingredient). Although it is also a nitrogen-fixing legume, its protein content is lower than that of gliricidia. This is largely due to the morphophysiological characteristics of the plant, which has a higher proportion of lignified stems in relation to the leaves, which dilutes the concentration of nitrogenous compounds in the total biomass (Tenakwa et al. 2022).

It is important to highlight that all the hays used were effective in increasing the CP content of the silages in relation to pure forage cactus silage, although in different magnitudes. This increase is of great relevance in the nutrition of ruminants in the semiarid region, since forage cactus, although abundant and strategic, has protein limitation that compromises rumen metabolism when supplied as exclusive roughage.

Regarding the fibrous fractions, a significant increase in the levels of NDF and ADF in silages with hay additives was expected, considering the low fiber content usually attributed to forage forage cactus (NDF = 26.87%) (Valadares Filho et al. 2018). However, the evaluation of the composition of the ingredients before ensiling revealed that the forage cactus used in the present study showed a high NDF value (407 g kg^{-1} DM), a result probably associated with the age of the plant at the time of harvest. The frequency of cutting, defined by the stage of growth in which the plants are used, exerts a strong influence on the bromatological composition: Older plants tend to have higher levels of NDF and ADF (Ramírez et al. 2007).

From this perspective, all silages presented NDF values above 300 g kg^{-1} DM. Nevertheless, when considering the ADF, there was a difference between the treatments: Forage cactus silage with silk flower hay presented the lowest value, reflecting the low content of this fraction in the hay itself, which reduced its contribution to the final mix.

Despite the absence of differences in NDF and NFC, the tCHO contents in the tested silages varied as a function of the redistribution of the other nutritional fractions, especially MM and CP. Thus, pigeon pea had the highest tCHO (740.8 g kg^{-1} DM) due to the lower levels of MM (94.8 g kg^{-1} DM) and CP (127.2 g kg^{-1} DM), increasing the portion of carbohydrates in DM. In contrast, silk flower exhibited the lowest tCHO (621.2 g kg^{-1} DM) due to relatively higher MM (172.9 g kg^{-1} DM) and CP (147.8 g kg^{-1} DM), which contracts the carbohydrate fraction (Sniffen et al. 1992).

However, it is important to highlight that the lower participation of tCHO in silage with silk flower did not translate into lower energy value, because the TDN is sensitive not only to the amount of carbohydrates but also to the digestibility of the fibrous fraction. Among the treatments, forage cactus silage with silk flower hay showed the highest TDN (≈627.7 g kg^{-1} DM). This superiority is due to the lower ADF content observed in this treatment (207.9 g kg^{-1} DM). Reductions in ADF indicate less recalcitrant cell walls, expand microbial access, and increase the rate and extent of fiber degradation, increasing DM digestibility and energy value (Owens et al. 2010; Raffrenato et al. 2017).

4.3 | *In Situ* Dry Matter Degradability

Pure forage cactus silage showed a modest soluble fraction (a = 20.05%) and a low degradable fraction degradation rate (c = 0.02 h^{-1}). This combination resulted in intermediate PD (PD = 53.81%) and progressively lower ED as the pass rate (k) increased, with values of 37.96%, 30.56%, and 27.48% for k = 0.02, 0.05, and 0.08 h^{-1}, respectively.

In mechanistic terms, the combination of moderate b and low c causes a significant part of the DM to leave the rumen undegraded, resulting in lower digestible energy under typical k (Ørskov and McDonald, 1979). This kinetic profile is consistent with the greater recalcitrance of the cell wall previously described for pure forage cactus silage, explaining the slow ascent of the degradation curves up to approximately 120 h (Figure 1).

On the other hand, the inclusion of hay in the forage cactus silage modified the rumen kinetics in two complementary axes: it raised a and, above all, it increased c, anticipating the plateau of the curves and reducing the penalty imposed by k on the ED. This adjustment is associated with the higher content of physically effective fiber, which prolongs the ruminal retention time and stabilizes the fermentation environment, favoring the degradation of b before passage (Grant 2023). In agreement with this pattern, Gomes et al. (2023) reported that the inclusion of pornunça silage in forage cactus-based diets increased a and increased both b and c. As a consequence, the ED was increased even at higher k, confirming that the association of the forage cactus with roughage of higher DM and NDF improves kinetics and minimizes ruminal nutrient escape.

This fact also occurred in the current study, since among the hays tested, the silk flower hay presented the most consistent performance, combining high (39.52%) and accentuated c (0.07 h^{-1}); as a consequence, it exhibited the highest ED in all k. This pattern is consistent with lower cell wall recalcitrance (lower ADF in the material), an association that the literature links to higher digestibility and energy value when the structural barrier is reduced (Riaz et al. 2014).

Gliricidia, although presenting lower b (18.59%), remained high ED and little sensitive to the increase in k thanks to the simultaneous increase in a (27.85%) and c (0.36 h^{-1}). In nutritional terms, this profile is relevant because it favors the synchronization between fermentable energy supply and nitrogen release, an essential condition to maximize the efficiency of ruminal microbial synthesis and nutrient utilization (Cuervo et al. 2025).

Pornunça showed intermediate behavior (moderate and high c), sustaining stable ED even with a lower b. Pigeon pea, on the other hand, gathered the worst indicators (low values of a and b, but with moderate c), resulting in the lowest ED.

These results are reflected in the curves presented in Figure 1, where the mixtures of forage cactus and hay, especially silk flower and gliricidia, quickly reached high levels of degradation. From an applied point of view, accelerating the rate of degradation is particularly relevant in semiarid systems, in which diets with a higher share of dry roughage raise k; by increasing c, mixtures with hay preserve the degradable fraction in the rumen long enough to be effectively used.

5 | Conclusion

The inclusion of hays from forage crops adapted to the semiarid region in the ensilage of forage cactus (cv. Giant) reduced gas and effluent losses, increased DM content, and provided more stable fermentation. This strategy increased the CP content, energy value, and ruminal degradability of the silages, with emphasis on the combinations with silk flower and gliricidia, which showed the highest degradation rates and best nutrient utilization.

These results indicate that forage cactus silage combined with these hays constitutes a practical and sustainable alternative for the production of high-quality roughage, capable of meeting the nutritional requirements of ruminants in arid and semiarid regions.

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Conflicts of Interest

The authors report there are no competing interests to declare.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Agricultural and Food Research Council (AFRC). 1993. *Energy and Protein Requirements of Ruminants: An Advisory Manual Prepared by AFRC Technical Committee on Responses to Nutrients*, CAB Int.

AOAC. 1990. "Official Methods of Analysis." 15th Ed. Arlington, VA, USA: Association of Official Analytical Chemists.

Bolsen, K. K., R. N. Sonon, B. Dalke, V. P. Ronald, G. R. Jack, and A. Laytimi. 1992. "Evaluation of Inoculant and NPN Silage Additives: A Summary of 26 trials and 65 Farm-Scale Silages." *Kansas Agricultural Experiment Station Research Reports* 1: 102–103. https://doi.org/10.4148/2378-5977.2192.

Borges, E. N., C. Almeida Araújo, B. S. Monteiro, et al. 2025. "Buffel Grass Pre-Dried as a Modulator of the Fermentation, Nutritional and Aerobic Stability Profile of Cactus Pear Silage." *New Zealand Journal of Agricultural Research* 68, no. 1: 100–115. https://doi.org/10.1080/00288233.2023.2212173.

Brito, G. S. M. S., E. M. Santos, G. G. L. Araújo, et al. 2020. "Mixed Silages of Cactus Pear and Gliricídia: Chemical Composition, Fermentation Characteristics, Microbial Population and Aerobic Stability." *Scientific Reports* 10: 1–13. https://doi.org/10.1038/s41598-020-63905-9.

Cappelle, E. R., S. C. Valadares Filho, J. F. C. Silva, and P. R. Cecon. 2001. "Estimates of the Energy Value from Chemical Characteristics of the Feedstuffs." *Revista Brasileira de Zootecnia* 30: 1837–1856. https://doi.org/10.1590/S1516-35982001000700022.

Cuervo, W., C. Gomez-Lopez, and N. DiLorenzo. 2025. "Methane Synthesis as a Source of Energy Loss Impacting Microbial Protein Synthesis in Beef Cattle – a Review." *Methane* 4, no. 2: 10. https://doi.org/10.3390/methane4020010.

Dall-Orsoletta, A. C., T. A. Reiter, G. V. B. Kozloski, V. Niderkorn, and H. M. N. Ribeiro Filho. 2017. "Associative Effects between Arachis Pintoi and Dwarf Elephantgrass Hays on Nutritional Value in Sheep." *Animal Production Science* 58: 894–899. https://doi.org/10.1071/AN15864.

Dubeux Júnior, JCB., MVF. Santos, M. V. Cunha, D. S. Cordeiro, RTA. Souza, and ACL. Mello. 2021. "Cactus (*Opuntia* and *Nopalea*) Nutritive Value: A Review." *Animal Feed Science and Technology* 275: 114890. https://doi.org/10.1016/j.anifeedsci.2021.114890.

Fradera-Soler, M., O. M. Grace, B. Jørgensen, and J. Mravec. 2022. "Elastic and Collapsible: Current Understanding of Cell Walls in Succulent Plants." *Journal of Experimental Botany* 73, no. 8: 2290–2307. https://doi.org/10.1093/jxb/erac054.

Gomes, M. L. R., J. R. V. da Silva Filho, F. C. Alves, et al. 2023. "In Situ Ruminal Degradability of Forage Cactus-Based Diets Associated with Pornunça Silage." *Semina: Ciências Agrárias* 44: e312689. https://doi.org/10.5433/1679-0359.2023v44n2p549.

Grant, R. J. 2023. "Symposium Review: Physical Characterization of Feeds and Development of the Physically Effective Fiber System." *Journal of Dairy Science* 106, no. 6: 4454–4463. https://doi.org/10.3168/jds.2022-22419.

Jobim, C. C., L. G. Nussio, R. A. Reis, and P. Schmidt. 2007. "Methodological Advances in Evaluation of Preserved Forage Quality." *Revista Brasileira de Zootecnia* 36: 101–119. https://doi.org/10.1590/S1516-35982007001000013.

Kaba, J. S., S. Zerbe, M. Agnolucci, et al. 2019. "Atmospheric Nitrogen Fixation by Gliricidia Trees (*Gliricidia Sepium* (Jacq.) Kunth Ex Walp.) Intercropped with Cocoa (*Theobroma Cacao* L.)." *Plant and Soil* 435: 323–336. https://doi.org/10.1007/s11104-018-3897-x.

Kung, L. Jr., R. D. Shaver, R. J. Grant, and R. J. Schmidt. 2018. "Silage Review: Interpretation of Chemical, Microbial, and Organoleptic Components of Silages." *Journal of Dairy Science* 101, no. 5: 4020–4033. https://doi.org/10.3168/jds.2017-13909.

Liu, Y., Z. Wang, L. Sun, et al. 2025. "Effects of Moisture Content Gradient on Alfalfa Silage Quality, Odor, and Bacterial Community Revealed by Electronic Nose and GC–MS." *Microorganisms* 13, no. 2: 381. https://doi.org/10.3390/microorganisms13020381.

McDonald, P., R. A. Edwards, J. F. D. Greenhalgh, C. A. Morgan, L. A. Sinclair, and R. G. Wilkinson. 2020. *Animal Nutrition*. 8th, ed. Pearson.

McDonald, P., A. R. Henderson, and S. J. E. Heron. 1991. *Biochemistry of Silage*. 2nd ed. Chalcombe Publ.

Nascimento, D. B., A. L. R. Magalhães, G. G. L. Araújo, et al. 2024. "Productive, Morphological and Nutritional Indicators of Cactus Pear in a Semiarid Region." *Agronomy* 14, no. 10: 2366. https://doi.org/10.3390/agronomy14102366.

Nocek, J. E. 1988. "In Situ and Other Methods to Estimate Ruminal Protein and Energy Digestibility: A Review." *Journal of Dairy Science* 71, no. 8: 2051–2069. https://doi.org/10.3168/jds.S0022-0302(88)79781-7.

Ogburn, R. M., and E. J. Edwards. 2010. "The Ecological Water-use Strategies of Succulent Plants." *Advances in Botanical Research* 55: 179–225. https://doi.org/10.1016/B978-0-12-380868-4.00004-1.

Oliveira, J. S., H. C. Mantovani, A. A. Rodrigues, I. M. Ferreira, and E. M. Santos. 2025. "Forage Cactus and the Growth of Pathogenic Microorganisms in Ruminants." *Journal of the Science of Food and Agriculture* 105: 6908–6916. https://doi.org/10.1002/jsfa.14266.

Ørskov, E. R., and I. McDonald. 1979. "The Estimation of Protein Degradability in the Rumen from Incubation Measurements Weighted According to Rate of Passage." *The Journal of Agricultural Science* 92, no. 2: 499–503. https://doi.org/10.1017/S0021859600063048.

Owens, F. N., D. A. Sapienza, and A. T. Hassen. 2010. "Effect of Nutrient Composition of Feeds on Digestibility of Organic Matter by Cattle – A Review." *Journal of Animal Science* 88, no. Suppl 13: E151–E169. https://doi.org/10.2527/jas.2009-2559.

Paul, B. K., J. C. J. Groot, B. L. Maass, A. Notenbaert, M. Herrero, and P. Tittonell. 2020. "Tropical Forage Technologies Can Deliver Multiple Benefits in Sub-Saharan Africa." *Agronomy for Sustainable Development* 40, no. 2: 26. https://doi.org/10.1007/s13593-020-00626-3.

Paulino, R. S., J. S. de Oliveira, E. M. Santos, et al. 2021. "Spineless Cactus use Management on Microbiological Quality, Performance, and Nutritional Disorders in Sheep." *Tropical Animal Health and Production* 53: 168. https://doi.org/10.1007/s11250-021-02594-6.

Playne, M. J., and P. McDonald. 1966. "The Buffering Constituents of Herbage and Silage." *Journal of the Science of Food and Agriculture* 17, no. 6: 264–268. https://doi.org/10.1002/jsfa.2740170609.

Quintero-Anzueta, S., I. C. Molina-Botero, J. S. Ramirez-Navas, et al. 2021. "Nutritional Evaluation of Tropical Forage Grass Alone and Grass-Legume Diets to Reduce In Vitro Methane Production." *Frontiers in Sustainable Food Systems* 5: 663003. https://doi.org/10.3389/fsufs.2021.663003.

Raffrenato, E., R. Fievisohn, K. W. Cotanch, R. J. Grant, L. E. Chase, and M. E. Van Amburgh. 2017. "Effect of Lignin Linkages with Other Plant Cell Wall Components on In Vitro and In Vivo NDF Digestibility and Rate of Digestion of Grass Forages." *Journal of Dairy Science* 100, no. 10: 8119–8131. https://doi.org/10.3168/jds.2016-12364.

Ramírez, H. M. T., J. A. A. Reyes, J. M. R. Pinos, and J. R. R. Aguirre. 2007. "Efecto De LA Especie y Madurez Sobre El Contenido De Nutrientes De Cladodios De Nopal." *Agrociencia* 41: 619–626.

Riaz, M. Q., K. H. Südekum, M. Clauss, and A. Jayanegara. 2014. "Voluntary Feed Intake and Digestibility of Four Domestic Ruminant Species as Influenced by Dietary Constituents: A Meta-Analysis." *Livestock Science* 162: 76–85. https://doi.org/10.1016/j.livsci.2014.01.009.

Rodrigues, R., R. Lopes, F. N. Santos, et al. 2023. "Total Mixed Ration Silages Based on Forage Cactus and Xerophile Legumes as Alternatives for Ruminants." *Agriculture* 13: 1759. https://doi.org/10.3390/agriculture13091759.

Sá, M. K. N., A. P. de Andrade, G. G. L. de Araújo, et al. 2024. "Fermentation Profile, Aerobic Stability, and Chemical and Mineral Composition of Cactus Pear Silages with Different Inclusion Levels of Gliricidia Hay." *Plants* 13: 195. https://doi.org/10.3390/plants13020195.

Santos, S. A., H. E. Santana, M. S. Jesus, et al. 2024. "Progress and Trends in Forage Cactus Silage Research: A Bibliometric Perspective." *Fermentation* 10: 531. https://doi.org/10.3390/fermentation10100531.

Schultze-Kraft, R., I. M. Rao, M. Peters, R. J. Clements, C. Bai, and G. Liu. 2018. "Tropical Forage Legumes for Environmental Benefits: An Overview." *Tropical Grasslands-Forrajes Tropicales* 6, no. 1: 1–14. https://doi.org/10.17138/tgft(6)1-14.

Sniffen, C. J., J. D. O'Connor, P. J. Van Soest, D. G. Fox, and J. B. Russell. 1992. "A Net Carbohydrate and Protein System for Evaluating Cattle Diets: II. Carbohydrate and Protein Availability." *Journal of Animal Science* 70, no. 11: 3562–3577. https://doi.org/10.2527/1992.70113562x.

Tenakwa, E. A., A. Z. Imoro, T. Ansah, and F. Kizito. 2022. "Pigeon Pea (*Cajanus Cajans*) Fodder Cutting Management in the Guinea Savanna Agro-Ecological Zone of Ghana." *Agroforestry Systems* 96, no. 1: 1–10. https://doi.org/10.1007/s10457-021-00679-7.

Theander, O., and E. A. Westerlund. 1986. "Studies on Dietary Fiber. 3. Improved Procedures for Analysis of Dietary Fiber." *Journal of Agricultural and Food Chemistry* 34, no. 2: 330–336. https://doi.org/10.1021/jf00068a045.

Valadares Filho, S. C., S. A. Lopes, B. C. Silva, M. L. Chizzotti, and L. Z. Bissaro. 2018. *CQBAL. 4.0. Tabelas Brasileiras De Composição De Alimentos Para Ruminantes*. CQBAL.

Van Soest, P. V., J. B. Robertson, and B. A. Lewis. 1991. "Methods for Dietary Fiber, Neutral Detergent Fiber, and Nonstarch Polysaccharides in Relation to Animal Nutrition." *Journal of Dairy Science* 74, no. 10: 3583–3597. https://doi.org/10.3168/jds.S0022-0302(91)78551-2.

Vieira, D. S., J. S. de Oliveira, E. M. Santos, et al. 2022. "Microbiological Composition of Diets of Cactus Pear-Based with Increasing Levels of Buffel Grass Hay and Relationship to Nutritional Disorders in Sheep." *Animals* 12: 500. https://doi.org/10.3390/ani12040500.

Zanine, A. M., E. M. Santos, J. R. R. Dorea, P. A. S. Dantas, T. C. Silva, and O. G. Pereira. 2010. "Evaluation of Elephant Grass Silage with Addition of Cassava Scrapings." *Revista Brasileira de Zootecnia* 39, no. 12: 2611–2616. https://doi.org/10.1590/S1516-35982010001200008.