

Article

Spineless Cactus (*Opuntia stricta* and *Nopalea cochenillifera*) with Added Sugar Cane (*Saccharum officinarum*) Bagasse Silage as Bovine Feed in the Brazilian Semi-Arid Region

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Simple Summary

This study examined the effectiveness of silage made from spineless forage cactus mixed with sugarcane bagasse as animal feed. Good feed is essential for healthy and productive livestock, especially in areas where food quality fluctuates significantly. Different amounts of bagasse were tested (0, 150, 300, 450, and 600 g/kg dry matter), mixed with cactus and a small amount of urea. It was found that silage made only from cactus produced gas differently from silage with bagasse, which showed very little gas production at first. Adding bagasse reduced how well the silage broke down in the lab, lowering its dry and organic matter digestibility and gas production as bagasse levels increased. However, silage with 150 g/kg of bagasse treated with urea provided a good balance between the required energy and fiber. Overall, this cactus–bagasse mix could be a low-cost, sustainable feed option for ruminant animals.

Abstract

The success of optimal ruminant production relies heavily on feed efficiency to deliver the necessary nutrients to animals. Nutritional deficiencies in livestock pose a significant challenge in regions experiencing prolonged fluctuations in resource availability and quality. In this context, the present study aimed to investigate the cumulative gas production (CGP) and in vitro degradability of silages made from spineless forage cactus (a native species) combined with high-fiber ingredients, to evaluate their viability as a sustainable, low-cost alternative to animal feed. The experiment involved ensiling spineless cactus genotypes with varying levels of sugarcane bagasse (0, 150, 300, 450, and 600 g/kg of dry matter) and a 1% urea–ammonium sulfate solution. The results indicated that for all genotypes studied,



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the CGP curves from silage composed solely of forage cactus differed significantly from those containing bagasse, which exhibited an initial phase characterized by little or no gas production. In vitro degradability was negatively influenced by the inclusion of bagasse at any level, resulting in decreased dry matter and organic matter degradability, as well as reduced CGP with increasing bagasse concentration. Therefore, the study demonstrated that the proposed combination of ingredients represents a promising sustainable feed supplement to enhance animal nutrition. Silage containing 150 g/kg of bagasse treated with urea offers a favorable balance between the energy required by rumen microflora and the benefits of fiber presence.

Keywords: animal nutrition; cumulative gas production; feed; forage cactus; semi-arid; silage; sugarcane bagasse

1. Introduction

Livestock farming is an important socio-economic activity that supports many livelihoods in the Brazilian semi-arid region (Figure 1). Certain animal species, such as small ruminants, are well adapted to harsh environmental conditions, making them more resilient to the impacts of the climate change characteristic of the area [1]. However, since ruminant production systems in these regions rely primarily on forage plants, they are highly dependent on edaphoclimatic conditions [2]. The semi-arid climate is marked by prolonged dry seasons that exceed the length of the rainy periods, leading to difficulties in forage and grain production for animal feed and often resulting in economic vulnerability [3].



Figure 1. The Brazilian semi-arid region. Source: the authors.

To address the challenges posed by limited water resources and their impact on productivity, researchers have investigated and adjusted various factors to improve outcomes in arid environments [4]. Understanding the dynamics of the livestock feed supply chain in relation to specific soil and climate conditions allows for the optimization of production yields (e.g., pasture capacity) while minimizing environmental degradation [5]. Effective management of resources naturally suited to the local semi-arid climate has proven to be the most appropriate strategy. If developing breeding strategies can overcome some problems [6], conserving and expanding the cultivation of native forage species helps meet the nutritional needs of livestock while supporting the sustainability and viability of

production systems [5]. These diverse local forages are rich in essential nutrients and can offer a balanced diet, reducing dependence on commercial feed.

In this context, several alternative feeds have been proposed to replace traditional forages and starchy grains. Notable examples are the spineless cactus, *Opuntia stricta* Haw., and the *Nopalea cochenillifera* Salm Dyck, which have been identified as valuable components of ruminant fodder in arid and semi-arid regions [7]. In addition to their drought resistance and high potential for dry matter (DM) production per hectare, these cacti offers benefits such as high palatability and substantial nutritive value, including important levels of non-fiber carbohydrates (NFCs) (approximately 500 g/kg DM), water-soluble carbohydrates (WSCs) (150 g/kg) and total carbohydrates (TCs) (617–711 g/kg) [8,9]. However, the low concentrations of neutral detergent fiber (NDF) (approximately 250 g/kg) and crude protein (CP) (33 to 44 g/kg) [8] in cactus limit its use as a sole roughage source in ruminant diets. As a result, it is often necessary to combine it with other feed components to compensate for these nutritional deficiencies and create a balanced diet.

Mixing spineless cactus with plants rich in fiber or protein can help compensate for cactus's low DM content and improve its suitability for ensiling, a common technique used to store and preserve excess forage produced during wet seasons. This preserved forage can then be used to feed livestock during periods of scarcity [9]. Godoi et al. [10] explored the use of a mixed silage comprising spineless cactus and tropical forage plants (pornuça and gliricidia), in a 60:40 dry matter (DM) proportion, for feeding sheep. They demonstrated that this association improved nutrient intake and digestibility compared to using only cactus silage, which had an NFC content exceeding the recommended level in ruminant feed and a reduction in CP digestibility.

Non-fiber carbohydrates serve as a primary, readily available energy source due to their high digestibility and rapid degradation rate [11]. These carbohydrates play a key role in maximizing microbial protein synthesis and overall energy intake in ruminants. Among these carbohydrates, mucilage is present as a heterogeneous polysaccharide that functions as a hydrocolloid gum. This offers flexibility and high water retention capacity to the plant [12]. However, diets with high NFC levels can lead to acidosis [13], a condition that intensifies rumen fermentation and volatile fatty acid (VFA) production, resulting in a decrease in ruminal pH and imbalances in ruminal microbial flora and performance [14]. In contrast, fiber promotes chewing and rumination, which stimulate saliva secretion. Saliva helps neutralize ruminal acidity, thereby mitigating the negative effects of high NFC levels. This behavior supports proper rumen motility and fosters an environment conducive to improved microbial development and reproductive performance. Achieving optimal rumen health and metabolism requires a careful balance between energy-dense nutrients and dietary fiber [15].

Sustainable tropical forages can provide the necessary fiber to complement spineless cactus, including agro-industrial residues and crop by-products. Sugarcane bagasse, a byproduct of the sugar-alcohol industry and one of the most abundant agro-residues in Brazil, can be efficiently used as a sustainable fiber supplement. To maintain a low-cost and efficient diet, urea can be incorporated as a non-protein nitrogen (NPN) source to compensate for protein deficiencies in diets based on bagasse and forage cactus [16]. The combination of highly digestible carbohydrates, physically effective fiber, and NPN promotes energy–nitrogen synchronization, improving nutrient utilization and consequently animal performance [17].

Several studies have investigated the combination of forage cactus and sugarcane bagasse silage as a feed for ruminants, demonstrating improvements in animal performance and the provision of necessary nutritive value without compromising animal health. For instance, Lima et al. [18] evaluated four different fiber sources (corn silage, sorghum, hay, and bagasse) in combination with cactus for dairy goats. Similarly, Silva et al. [19] assessed

the impact of different levels of full-fat corn germ when combined with bagasse and cactus. Siqueira et al. [20], and Siqueira et al. [21] explored the use of two types of cactus with bagasse, comparing them to traditional silages. Furthermore, Medeiros et al. [22] and Ribeiro et al. [23] proposed the replacement of corn silage with cactus and bagasse in the diets of dairy cows and sheep. However, none of the reported studies have compared different levels of sugarcane bagasse and cactus in silages without the impact of other traditional roughage ingredients, such as Tifton hay and corn silage.

This study aimed to evaluate the effect of varying levels of urea-treated bagasse on the silages of three spineless cactus genotypes (*Orelha de Elefante Mexicana*-*Opuntia stricta* Haw., *Miúda*-*Nopalea cochenillifera* Salm Dick, and *Baiana*-*Nopalea cochenillifera* Salm Dick) with respect to ruminal fermentation kinetics and degradability, as estimated through in vitro cumulative gas production. The proper combination of cactus with sugarcane and urea can provide nutritional value similar to traditional roughages, providing energy and avoiding acidosis. The species *Opuntia stricta* and *Nopalea cochenillifera* are among the most cultivated in the semi-arid region due to their incredible adaptability to climatic conditions and their high productivity potential, even in comparison to other cacti. Both are utilized as animal feed, providing a short vegetative cycle and quick returns from an agronomic perspective. Particularly in the Brazilian semi-arid regions (caatinga), these species are emphasized due to their high resilience to stresses within productive systems, highlighting the interaction between species and systems [24,25].

This research is distinctive in providing a comprehensive comparative analysis of different bagasse inclusion levels and cactus genotypes to assess their impact on ruminal fermentation. This in-depth analysis can be decisive in selecting appropriate ingredient proportions for optimal feed formulations.

2. Materials and Methods

The experiments were conducted at the Food Analysis Laboratory of the Pernambuco Federal Institute of Education, Science, and Technology (Pernambuco, Brazil). The treatments consisted of forage cactus silage combined with five levels of sugarcane bagasse (0, 150, 300, 450, and 600 g/kg DM) and a 1% urea–ammonium sulfate solution (9:1 ratio). Three spineless forage cactus genotypes were used: *Orelha de Elefante Mexicana* (*Opuntia stricta* Haw., referred to as *Mexicana*), *Miúda* (*Nopalea cochenillifera* Salm Dick), and *Baiana* (*Nopalea cochenillifera* Salm Dick). This study evaluated various cactus genotypes to assess how their distinct chemical compositions affect their effectiveness as energy sources. Although all were cactus, genotypic differences were expected. Sugarcane was added as a fiber source to improve the overall content. The selected sugarcane levels were based on the recommended fiber threshold, ensuring they did not exceed 60% or 600 g/kg [26].

The ingredients were analyzed for dry matter (DM) (method 920.39), organic matter (OM) and mineral matter (MM) (method 942.05), ether extract (EE) (method 920.39), and crude protein (CP) (method 954.01), according to the methodology of the Association of Official Analytical Chemists [27]. The determination of neutral detergent fiber (NDF), acid detergent fiber (ADF), calcium (Ca), phosphorus (P), cellulose (CEL), hemicellulose (HEM), and lignin (LIG) was performed following the procedures described by Detmann et al. [28], adapted from Van Soest [29,30]. The results of individual ingredient compositions are presented in Table 1, while Table 2 displays the composition of the treatment combining cactus genotypes and sugarcane at various levels.

Table 1. Chemical–bromatological composition of silage from the genotypes of spineless cactus genotypes studies.

Variable (g/kg) ¹	Sugarcane Bagasse	Miúda ²	Baiana ²	Mexicana ²
DM	905.0	131.0	123.1	111.2
OM	911.2	935.0	921.5	901.2
NDF	866.7	254.5	234.3	278.0
ADF	583.9	222.5	191.2	240.8
EE	8.0	16.5	19.0	22.0
TCs	958.6	823.9	816.7	806.1
NFCs	91.9	569.4	582.4	528.1
Ash	150.0	113.1	121.3	131.9
CP	18.4	46.5	43.0	40.0
Ca	8.4	23.0	25.0	28.7
P	10.9	1.8	2.1	2.9
CEL	427.1	200.5	210.0	215.3
HEM	282.8	32.0	35.1	37.2
LIG	156.8	22.0	24.3	25.5

¹ g/kg of DM = dry matter; OM = organic matter; NDF = neutral detergent fiber; ADF = acid detergent fiber; EE = ether extract; TCs = total carbohydrates; NFCs = non-fiber carbohydrates; CP = crude protein; Ca = calcium; P = phosphorus; CEL = cellulose; HEM = hemicellulose; LIG = lignin. ² Spineless forage cactus genotype.

Table 2. Chemical–bromatological composition * of treatments with forage cactus silage combined with five levels of sugarcane bagasse (0, 150, 300, 450, and 600 g/kg DM).

SBL ¹ g/kg of DM	150	300	450	600	150	300	450	600	150	300	450	600
Cactus ²	<i>Miúda</i>				<i>Baiana</i>				<i>Mexicana</i>			
Variable ³												
DM	247.1	363.2	479.3	595.4	240.3	357.6	474.9	592.2	230.2	349.3	468.4	587.4
OM	931.4	927.8	924.2	920.7	919.9	918.4	916.8	915.3	902.7	904.2	905.7	907.2
NDF	346.3	438.1	529.9	621.8	329.1	424.0	518.8	613.7	366.30	454.6	542.9	631.2
ADF	276.7	330.9	385.1	439.3	250.1	309.0	367.9	426.8	292.2	343.7	395.1	446.6
EE	15.2	13.9	12.6	11.4	17.3	15.7	14.0	12.4	19.9	17.8	15.7	13.6
TCs	844.1	864.3	884.5	904.7	837.9	859.2	880.5	901.8	828.9	851.8	874.7	897.6
NFCs	497.7	426.1	354.5	282.9	508.8	435.2	361.6	288.1	462.6	397.2	331.8	266.3
Ash	118.6	124.1	129.7	135.2	125.6	129.9	134.2	138.5	134.6	137.3	140.0	142.7
CP	42.2	38.0	33.8	29.6	39.3	35.6	31.9	28.2	36.7	33.5	30.2	27.0
Ca	20.8	18.6	16.4	14.2	22.5	20.0	17.5	15.0	25.6	22.6	19.5	16.5
P	3.1	4.5	5.8	7.26	3.4	4.7	6.0	7.3	4.1	5.3	6.5	7.7
CEL	234.4	268.4	302.4	336.4	242.5	275.1	307.6	340.2	247.0	278.8	310.6	342.3
HEM	69.6	107.2	144.8	182.4	72.2	109.4	146.5	183.7	74.0	110.8	147.7	184.5
LIG	42.2	62.4	82.6	102.8	44.1	64.0	83.9	103.8	45.1	64.8	84.5	104.2

* Calculated based on the proportion of each individual ingredient used. ¹ Sugarcane bagasse level; ² Spineless forage cactus genotype; ³ g/kg of DM = dry matter; OM = organic matter; NDF = neutral detergent fiber; ADF = acid detergent fiber; EE = ether extract; TCs = total carbohydrates; NFCs = non-fiber carbohydrates; CP = crude protein; Ca = calcium; P = phosphorus; CEL = cellulose; HEM = hemicellulose; LIG = lignin.

The proportions of total carbohydrates (TCs) and non-fiber carbohydrates (NFCs), also shown in Table 1, were estimated based on the assumption that the sum of carbohydrates, fiber, ash, ether extract, and crude protein represents the complete centesimal composition of the feed [28]. The total carbohydrates were calculated using the equation $TC (\%) = 100 - [CP + EE + MM]$, as suggested by Sniffen et al. [31], and NFC using the formula proposed by Weiss et al. [32]: $NFC (\%) = 100 - [NDF + CP + EE + MM]$.

Silages were prepared in 4 L-capacity PVC microsilos. Each treatment, containing specific ingredient proportions, was ensiled for 60 days. The experiment assessed ruminal

fermentation kinetics using the semi-automatic in vitro gas production technique [33]. Samples (1 g) were incubated in 160 mL glass flasks pre-flushed with CO₂ and stored at 4 °C to prevent undesirable fermentation before inoculation. Five hours before the start of the experiment, the flasks were transferred from the refrigerator to an oven at 39 °C, where they remained until inoculation.

The ruminal inoculum was obtained from five bovines after slaughter and evisceration at a slaughterhouse in Floresta (Pernambuco, Brazil). These animals were part of the municipal slaughter routine. The bovines were fed a diet of forage cactus, sugarcane bagasse, Tifton hay, and urea for 15 days prior to slaughter. The procedure is considered normal husbandry practice and does not raise any ethical concerns. As such, ethical approval was waived by the Ethics Committee (ORBEA) of IPVC. In the laboratory, the rumen fluid was filtered through cotton gauze under continuous CO₂ flushing and maintained in a water bath at 39 °C. Control samples consisted of flasks containing only rumen fluid and culture medium (90 mL), prepared following the methodology of Theodorou et al. [34]. The culture medium consisted of macro- and micro-mineral solutions, resazurin, and a bicarbonate buffer solution (NH₄HCO₃, NaHCO₃, and distilled water). Oxygen levels in the medium were decreased by adding a solution containing cysteine–HCl and Na₂S [35].

For analysis and experiment monitoring, the flasks were removed from incubation after intervals of 6, 12, 24, 48, and 96 h of fermentation. All treatments were replicated 10 times, and in every pre-defined interval, the volume of generated biogas of two samples per treatment was measured, totaling 150 experimental samples. To determine dry matter (DM) content, residues were filtered in crucibles with porosity 1 (Pirex-Vidrotec, São Paulo, Brazil) and dried in an oven at 100 °C for 48 h. The pressure of the gases accumulated in each sample was measured using a pressure transducer (Pressurte Press DATA 800, LANA, CENA-USP, Piracicaba, Brazil) connected to a needle (0.6 mm). The obtained pressure (P) (pounds per square inch) was converted into the volume of gas (mL) through the quadratic equation $V \text{ (mL)} = 0.17454 P^2 + 0.00315$, as suggested by Pereira et al. [36]. Correlations were estimated between the in vitro and in vivo results.

The cumulative gas production data were analyzed using a bicompartamental model proposed by Schofield et al. [37]:

$$V(t) = \frac{V_{f1}}{[1 + e^{(2-4 \times m_1(L-T))}]} + \frac{V_{f2}}{[1 + e^{(2-4 \times m_2(L-T))}]} \quad (1)$$

in which $V(t)$ = total maximal volume of gases produced; V_{f1} = maximal volume of gas for the rapidly digested fraction (NFC); V_{f2} = maximal volume of gas for the slowly digested fraction (FC); m_1 = specific growth rate for the rapidly degraded fraction (NFC); m_2 = specific growth rate for the slowly degraded fraction (FC); L = duration of the initial events of digestion (colonization time); T = fermenting time

Statistical analyses were performed using the NLIN (nonlinear regression) procedure in SAS version 9.1 [38]. The cumulative gas production data were also analyzed using the PROC MIXED procedure in SAS version 9.1 [38], with a significance level of 0.05 for type I error. Means were compared using Dunnett's test and orthogonal contrasts. The contrasts applied were as follows:

- I—Linear effect of sugarcane bagasse level;
- II—Quadratic effect of sugarcane bagasse level;
- III—Cubic effect of sugarcane bagasse level.

3. Results

Table 3 and Figures 2–4 show the variation in cumulative gas production (CGP) with the inclusion of sugarcane bagasse in forage cactus silage, where all evaluated genotypes

were significantly affected. The highest CGP values were observed with the inclusion of 150 g/kg of bagasse. As the bagasse level increased, CGP values declined, reaching the lowest point at 450 g/kg for Mexicana and at 600 g/kg for *Miúda* and *Baiana*.

Table 3. Cumulative gas production (mL/g of DM) from silage of three forage cactus genotypes studied associated with different sugarcane bagasse levels.

Cactus Genotype	Sugarcane Bagasse Inclusion Level (g/kg DM)					<i>p</i> -Value Bagasse Level
	0	150	300	450	600	
<i>Miúda</i>	93.0 A,b	30.2 B,b	10.0 C,b	7.9 D,b	4.6 E,b	<0.001
<i>Mexicana</i>	72.5 A,c	7.5 B,c	5.9 C,c	3.6 C,c	4.7 C,b	<0.001
<i>Baiana</i>	116.1 A,a	34.7 B,a	23.4 C,a	11.7 D,a	11.0 D,a	<0.001
<i>p</i> -Value genotype	<0.001	<0.001	<0.001	0.002	0.015	

Notes: Different letters in superscript are indicative of significant differences ($p < 0.05$) between genotypes (a, b, c, in columns) and levels of bagasse inclusion (A, B, C, D, E, in rows), after the Dunnett post hoc test.

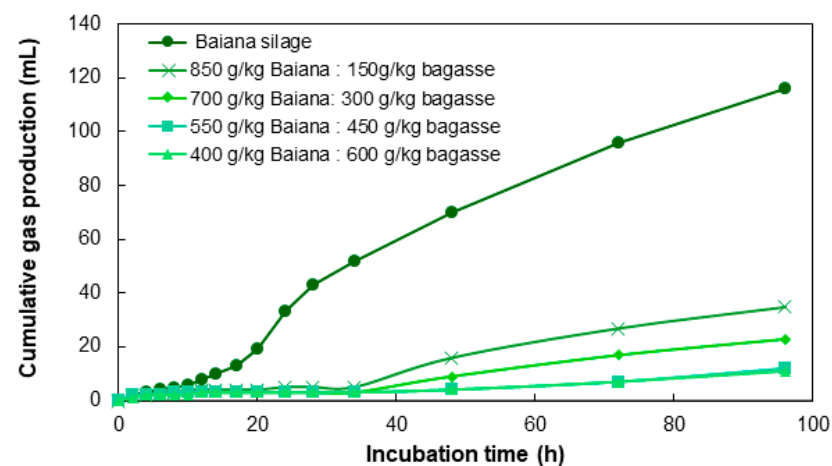


Figure 2. Cumulative gas production from the spineless forage cactus (*Nopalea cochenillifera*, cv *Baiana*) diets with different sugarcane bagasse levels added.

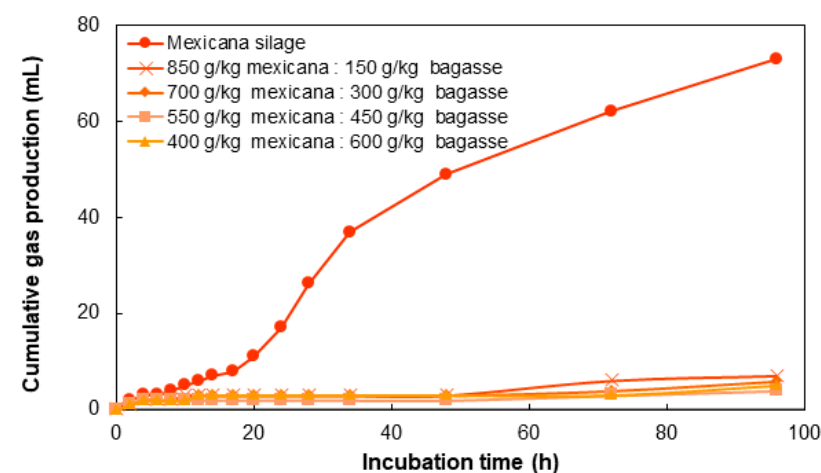


Figure 3. Cumulative gas production (CGP) from the spineless forage cactus (*Opuntia stricta*, cv *Mexicana*) diets with different sugarcane bagasse levels added.

Among the three evaluated forage cactus genotypes, the inclusion of bagasse at any level negatively affected silage dry matter (DM) and organic matter (OM) degradability, both of which decreased as the bagasse content increased. The highest in vitro degradability coefficients of DM were recorded in silages without bagasse: 823.9 g/kg DM for *Baiana* and 862.29 g/kg DM for *Miúda*. The lowest degradability value was 116.6 g/kg DM in *Baiana* silage with 600 g/kg of bagasse.

The maximum in vitro degradability of organic matter (IVDOM) was 956.29 g/kg DM for *Baiana* and 922.29 g/kg DM for *Mexicana*. In contrast, the lowest IVDOM was 199.47 g/kg DM, observed in *Miúda* silage with 600 g/kg of bagasse included (Table 4).

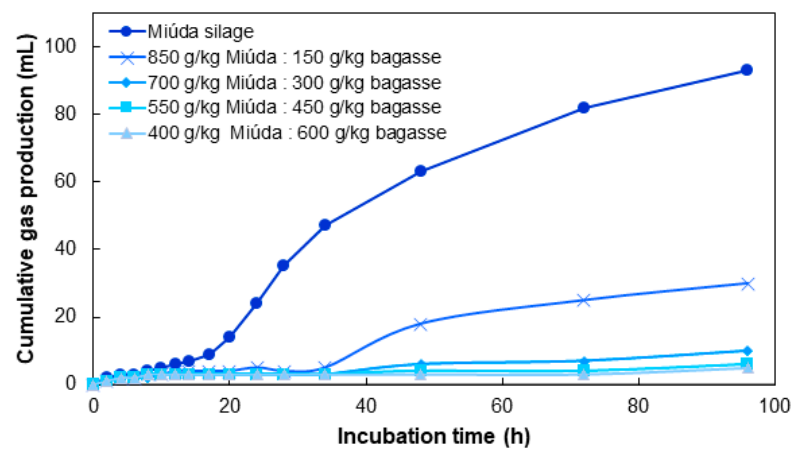


Figure 4. Cumulative gas production (CGP) from the spineless forage cactus (*Nopalea cochenillifera*, cv *Miúda*) diets with different sugarcane bagasse levels added.

Table 4. In vitro degradability of dry matter (IVDDM) and organic matter (IVDOM) from silage of the three forage cactus genotypes (*Miúda*, *Mexicana*, and *Baiana*) studied, associated with different sugarcane bagasse levels.

<i>Miúda</i> Forage								
Variable	Sugarcane Bagasse Inclusion Level (g/kg DM)					Contrast (<i>p</i> -Value)		
	0	150	300	450	600	Linear	Quadratic	Cubic
IVDDM (g/kgDM)	796.8 ^{b,A}	380.4 ^{a,B}	226.8 ^{b,C}	191.4 ^{b,D}	143.0 ^{a,E}	<0.001	0.107	0.801
IVDOM (g/kgDM)	862.9 ^{γ,Γ}	512.1 ^{β,Δ}	344.4 ^{γ,Θ}	294.8 ^{γ,Λ}	199.5 ^{γ,Ω}	<0.001	0.171	0.649
<i>Mexicana</i> Forage								
Variable	Sugarcane Bagasse Inclusion Level (g/kg DM)					Contrast (<i>p</i> -Value)		
	0	150	300	450	600	Linear	Quadratic	Cubic
IVDDM (g/kgDM)	767.3 ^{b,A}	239.8 ^{c,B}	135.0 ^{c,D}	122.5 ^{c,D}	151.2 ^{a,C}	<0.001	0.079	0.803
IVDOM (g/kgDM)	922.3 ^{β,Γ}	466.3 ^{γ,Δ}	433.1 ^{β,Θ}	441.6 ^{β,Θ}	360.8 ^{α,Λ}	0.024	0.746	0.420
<i>Baiana</i> Forage								
Variable	Sugarcane Bagasse Inclusion Level (g/kg DM)					Contrast (<i>p</i> -Value)		
	0	150	300	450	600	Linear	Quadratic	Cubic
IVDDM (g/kgDM)	823.9 ^{a,A}	310.7 ^{b,B}	278.7 ^{a,C}	233.8 ^{a,D}	116.6 ^{b,E}	0.001	0.836	0.398
IVDOM (g/kgDM)	956.3 ^{α,Γ}	647.4 ^{α,Δ}	507.6 ^{α,Θ}	475.3 ^{α,Λ}	320.4 ^{β,Ω}	0.015	0.848	0.562

Notes: Different letters in superscript are indicative of significant differences ($p < 0.05$) between genotypes for IVDDM (a, b, c, in columns) and IVDOM (α , β , γ in columns), and levels of bagasse inclusion for IVDDM (A, B, C, D, E, in rows) and IVDOM (Γ , Δ , Θ , Λ , Ω , in rows), after the Dunnett post hoc test.

4. Discussion

This study examined the effect of ensiling forage cactus with four different levels of bagasse on cumulative gas production (CGP) and the degradability of dry and organic matter. As shown in the CGP curves in Figures 2–4, the addition of bagasse decreases CGP across all evaluated forage cactus genotypes. A statistical analysis revealed a significant linear negative correlation between OM and DM degradability and bagasse level (Table 4). After analysis, the regression results showed that the linear model consistently demon-

strated a clear inverse relationship: when the bagasse level increased, the degradability and CGP decreased proportionally.

Gas production in the rumen is a direct result of the fermentation process by rumen microbes, wherein fast-degrading carbohydrates are primarily converted into volatile fatty acids (acetate, propionate, and butyrate), and gases such as methane and carbon dioxide [39]. Gas production can be impacted by lowering the NFC content and when carbohydrates are primarily fermented by lactic acid bacteria (LAB), leading to the inhibition of methanogens [39]. In this study, the observed gas reduction was primarily attributed to the addition of bagasse, which lowered the NFC content. The observed high *in vitro* digestibility in treatments with lower levels of bagasse reflects a positive correlation between gas production and OM and DM degradability. A significant interaction ($p < 0.05$) was also observed between incubation time and treatments (Table 3). The notable effect of time is clear in the cumulative gas production curves.

Analysis of the cumulative gas curves revealed significant differences between silages with bagasse inclusion and those composed solely of forage cactus, although differences among genotypes were relatively minor. Nonetheless, the influence of NFC concentration was also observed when comparing cactus genotypes, with *Baiana*, which had the highest NFC content, showing slightly higher cumulative gas production (Table 2). These observations support the observation that the higher the concentration of NFC in cactus-based silage, the higher the gas production.

The cactus genotype is particularly rich in heteropolysaccharides, mucilage, and cell-wall pectin [40]. Magalhães et al. [41] reported that *Napolea cochenillifera* Salm-Dick and *Opuntia stricta* Haw have pectic contents of 382 and 155 g/kg DM, respectively, which positively influences gas production from fermentable carbohydrates [13,42]. Furthermore, an increase in indigestible components at the expense of NFC, protein, and other nutrients compromises the energy substrate available to ruminal microorganisms, hindering microbial protein synthesis [43]. Consequently, the inclusion of bagasse, which dilutes the proportion of cactus, limits the availability of degradable carbohydrates and organic matter, reducing the energy content and thus microbial growth.

Several factors influence feed degradability rates, including feed composition, particle size, the physical properties of the fiber, microbial populations, and the degradability of the plant cell wall [44]. However, low concentrations of NDF, ADF, and lignin along with a high carbohydrate fraction are expected to contribute to greater degradation and consequently increased gas production [41,42]. Some reduction in organic matter degradability in diets containing forage cactus may be explained by insufficient ruminal ammonia nitrogen, especially when combined with high fiber content. This is critical because cellulolytic microorganisms rely on both ruminal ammonia and carbon skeletons to stimulate microbial protein synthesis. Additionally, synchronization between energy molecules and proteins is crucial for maximizing microbial efficiency [45].

For samples containing only *Baiana*, *Mexicana*, or *Miúda* cactus, the initial phase was characterized by little or no gas production, followed by a rapid increase during the second phase, which lasted from 12 to 72 h, indicative of effective enzymatic breakdown. The expected decline in gas production rate, marking the asymptotic phase, began after 72 h of incubation. During the initial hours of fermentation, the digestible components of the substrate are immediately fermented. As the process continues, a small amount of material becomes hydrated and colonized by rumen microorganisms. These microorganisms generate varying degradation rates, dependent on the concentration of carbohydrates and the structural composition of the substrate [46]. Pure cactus silage exhibited similar fermentation behavior but with differences in value attributed to its distinct fermentable carbohydrate content and the presence of structural materials, as reported in Table 1.

In treatments with bagasse addition, a similar trend was observed; however, the initial phase was extended up to 36 h. The exponential phase then occurred between 36 and 72 h, followed by the asymptotic phase beginning after 72 h. The delayed initiation of gas production, with a longer lag phase, highlights the influence of the fiber content in the different treatments. The treatments based on the *qq* genotype showed an even more extended lag phase, likely due to its lower NFC content. All treatments with bagasse and *Mexicana* genotypes showed little gas production. Even at the lower tested inclusion level (150 g/kg), bagasse presence had a drastic impact on gas production when mixed with the *Mexicana* genotype, showing only slight gas production in both the initial fermentation phase and after substrate degradation by rumen microorganisms. As mentioned, the measured gas volume corresponds to the portion of the material that was digested. A higher lignin content increases the indigestible fraction of dry matter, thereby reducing the substrate's degradability rate. Thus, fibrous feeds rich in lignin, such as bagasse, are closely associated with reduced degradability and prolonged incubation periods. Moreover, NFCs are primarily responsible for gas production during the first 12 h of incubation, a critical period for microbial growth.

The degradation curves for *Miúda* + bagasse silage displayed different patterns. The treatments with 850 g/kg of *Miúda* and 150 g/kg of bagasse showed initial fermentation periods from 0 to 33 h and 0 to 18 h, respectively, followed by exponential phases from 33 to 48 h and 18 to 48 h. Both treatments exhibited a decline in gas production after 48 h of incubation. *Baiana* samples were found to be less impacted by the inclusion of bagasse when compared to *Mexicana* and *Miúda* at all levels of treatment, although the presence of bagasse also led to a decrease in gas production, especially when combined with 450 g/kg and 600 g/kg bagasse. As expected, the higher the bagasse content, the lower the total cumulative gas production. The CGP, fermentation, and substrate degradation curves exhibit a sigmoidal shape, typically characterized by three distinct phases: the initial phase (hydration, microbial attachment, and colonization), the exponential phase (rapid gas production due to enzymatic degradation), and the asymptotic phase (slowing gas production) [47].

The effect of bagasse in reducing DM and OM degradability, and consequently CGP, is attributed to the low degree of synchronization between the energy and nitrogen released to cellulolytic bacterial populations in the rumen [48]. Bacterial species that degrade soluble carbohydrates typically exhibit faster growth rates and higher fermentative efficiency compared to fiber-degrading bacteria. Additionally, the degradation rate depends on substrate solubility, as well as microbial growth and colonization efficiency [49].

Overall, by examining the effect of replacing varying levels of forage cactus silage (150–600 g/kg of dry DM) with sugarcane bagasse, as proposed in this study, it was possible to demonstrate that this combination holds potential as a feed supplement for animal nutrition. Among the evaluated treatments, forage cactus silage of *Baiana* and *Miúda* genotypes containing 150 g/kg DM of bagasse treated with urea showed promising results. These treatments achieved a favorable balance between readily available carbohydrates, which provide the energy needed for rumen microflora, and fiber content, which supports a healthy ruminal environment during fermentation and digestion. Although the inclusion of bagasse led to a significant decrease in CGP, DM, and OM degradability, its presence is important to avoid acidosis of ruminants. Nevertheless, future research should explore the effects of including bagasse at levels below 150 g/kg. Also, lower levels of fiber content must be explored to evaluate the performance of the *Mexicana* genotype, which was deeply impacted by bagasse.

5. Conclusions

The silages produced from the three evaluated spineless forage cactus genotypes have proven to be viable sustainable alternatives for animal feed. The results indicate that the inclusion of sugarcane bagasse (at any level) reduces cumulative gas production and organic matter degradability across all genotypes. However, treatments combining *Baiana* and *Miúda* forage cactus with 150 g/kg of bagasse and 1% urea can be recommended as a potential feed supplement during periods of feed scarcity, particularly in arid and semi-arid regions. Meanwhile, for the *Mexicana* genotype, which was deeply impacted by bagasse, a lower level should be evaluated.

This combination helps fulfill energy, fiber, and non-protein nitrogen requirements in the ruminant diet while offering a cost-effective and sustainable alternative to conventional roughage sources such as corn bran and soybean meal. Additionally, such supplemented diets may contribute to mitigating greenhouse gas emissions by enabling livestock to reach slaughter weight at a younger age, thereby shortening the production cycle.

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Abbreviations

The following abbreviations are used in this manuscript:

ADF	Acid detergent fiber
CEL	Cellulose
CGP	Cumulative gas production
CP	Crude protein
DM	Dry matter
EE	Ether extract
HEM	Hemicellulose

IVDDM	In vitro degradability of dry matter
IVDOM	In vitro degradability of organic matter
LIG	Lignin
NDF	Neutral detergent fiber
NFCs	Non-fiber carbohydrates
NPN	Non-protein nitrogen
OM	Organic matter
TCs	Total carbohydrates
TDNs	Total digestible nutrients
VFA	Volatile fatty acid

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