Babassu Byproducts in Total Mixed Ration Silage Based on Sugarcane for Small Ruminants Diets

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Abstract: The aim of the present study was to evaluate the fermentative profile, chemical composition, and in situ degradability of total mixed ration silage with or without babassu byproducts formulated for sheep diets. The experiment was performed in a completely randomized design, with four treatments (silages) and five replications (silos). The treatments were SS: sugarcane silage (control); SSCS: sugarcane silage with corn and soybean meal; SSBF: sugarcane silage with corn, soybean meal, and babassu flour; and SSBC: sugarcane silage with corn, soybean meal, and babassu cake. The experimental diets were formulated to be isoprotein, and to meet the nutritional requirements of confined sheep with an average weight of 20 kg, according to Nutrient Requirements of Small Ruminants. The SSCS, SSBF, and SSBC treatments presented the highest values of dry matter recovery (83.74, 82.08, and 83.92%, respectively), and higher dry matter (349.07, 344.39, and 352.32 g/kg, respectively), crude protein (151.19, 136.98, and 142.14 g/kg DM, respectively), and non-fibrous carbohydrate (444.70, 353.40, and 371.30 g/kg DM, respectively) contents than the SS treatment. The largest degradations of DM, CP, and neutral detergent fiber in each treatment occurred at 72 h, in which the SSCS treatments presented the highest degradations in comparison to the others (80.59, 87.89, and 55.68, respectively). The inclusion of babassu byproducts in sugarcane silages in the form of total ration acted positively in the qualitative indicators of the silages, improving the fermentation profile and reducing losses, as well as improving the chemical composition and in situ degradability.

Keywords: chemical composition; in situ degradability; losses

1. Introduction

Sugarcane silage is a challenge due to the elevated levels of soluble carbohydrates present in its composition, which cause alcoholic fermentation, resulting in high dry matter losses, high ethanol content, and loss of animal performance [1,2]. In addition, sugarcane silage has nutritional limitations, such as low protein content, low fiber availability, and low dry matter (DM) intake [3].

Thus, it is necessary to use technologies to overcome these problems. Some studies have been performed aiming to reduce undesirable fermentation and, consequently, minimize losses of dry matter and nutritional value, and increase the aerobic stability of sugarcane silage; however, the results of the use of microbiological additives are still inconsistent and controversial [4,5].

One of the technologies that can overcome the problems related to sugarcane silage is total mixed ration silage (TMRS). TMRS consists of a combination of forage with all
concentrate components in silage making, and has been successfully disseminated around the entire world [6–8]. Furthermore, this strategy has been efficient and viable to control the spoilage in feeds that have high moisture content, in addition to providing desirable conservation characteristics [9,10].

The use of byproducts in the silages can function as additives that inhibit undesirable fermentation. In the north–northeast region of Brazil, the babassu coconut (Orbignya sp.) has been processed, generating some oil types as well as several byproducts with potential for ruminant feeding [11]. These babassu byproducts can improve the fermentative profile and the nutritional value of sugarcane silage. Babassu byproducts increase DM, promoting decreased water activity, and causing the decreased action of ethanol producers’ yeasts. Higher DM also favors heterofermentative bacteria that can produce antifungal agents, while at the same time guaranteeing the preservation of the ensiled mass, increasing the recovery of dry matter and aerobic stability [12].

The babassu cake comes from the mechanical pressing of the babassu kernels for oil extraction, and babassu flour is obtained from a mechanized process of the mesocarp, and can have different textures and granulometry. Furthermore, there are still few publications on the use of babassu byproducts—especially those used in association with sugarcane in the form of TMRS for the evaluation of chemical characteristics, fermentative profiles, and ruminal degradation kinetics. However, there are an increasing number of studies evaluating the use of babassu byproducts in the diets of ruminants [11,13]. Therefore, the TMRS can replace the traditional total mixed ration and the daily mixture of silage with the concentrates, in addition to solving the problem of excess soluble carbohydrates and alcoholic fermentation, due to the absorbent action of the concentrate [3].

Therefore, the object of this study was to investigate the fermentative profile, chemical composition, and in situ degradability of TMRS with or without babassu byproducts in formulated diets for sheep.

2. Materials and Methods

The experiment was performed at the Center for Agricultural and Environmental Sciences of the Federal University of Maranhão in the municipality of Chapadinha, Baixo Parnaíba Region, Brazil, located at 03° 44′ 33″ S latitude, and 43° 21′ 21″ W longitude. The region’s climate is classified according to Köppen and Geiger [14] as warm tropical (Aw type), with a rainy season from November to March and an average rainfall of 1670 mm year⁻¹.

2.1. Experimental Design

The experimental design used was completely randomized, with four treatments (silages) and five replications (silos). Table 1 shows the composition of babassu byproducts. Silages in the form of total mixed ration silage (TMRS) were composed of 50% sugarcane and 50% concentrate, except for the control, which was only sugarcane silage (SS). The concentrates were based on corn and soybean (SSCS), replacing 50% of corn with babassu mesocarp flour (SSBF), and replacing 50% of corn with babassu cake (SSBC).

The experimental diets were formulated to be isoprotein, and to meet the nutritional requirements of confined sheep with an average weight of 20 kg, for a daily weight gain of 200 g/day, according to Nutrient Requirements of Small Ruminants (NRC, 2007) [15] (Table 1).

2.2. Preparation and Ensiling of Experimental Diets

For the ensiling process, the sugarcane was cut off at approximately 10 cm from the ground and chopped in a stationary forage machine, after which it was manually mixed with the concentrate ingredients. Then, the ensilage was carried out in silos with a capacity of 3 L, equipped with a Bunsen valve to release the gases. In each bucket was placed 1 kg of common sand used in construction material, dehydrated and separated from the material by a piece of fabric to prevent microbial contamination. After that, the quantification of the effluent was performed. Then, the compaction was carried out, and the silos were weighed,
sealed with a plastic lid, and wrapped with adhesive tape. The chemical composition of the diets at the time of ensiling is presented in Table 2.

Table 1. Chemical composition of babassu byproducts of the experimental diets (g/kg DM).

| Item (g/kg DM)         | Babassu Byproducts | Babassu Flour | Babassu Cake |
|------------------------|--------------------|---------------|--------------|
| Dry matter             | 874.96             | 889.22        |
| Mineral matter         | 30.88              | 41.84         |
| Organic matter         | 969.12             | 958.16        |
| Crude protein          | 52.40              | 155.16        |
| NDFap \textsuperscript{a} | 660.52            | 635.68        |
| ADFp \textsuperscript{b} | 547.84            | 537.20        |
| Hemicellulose          | 112.67             | 98.48         |
| Cellulose              | 379.83             | 433.33        |
| Lignin                 | 168.01             | 103.87        |
| Ether extract          | 242.60             | 118.07        |
| Total carbohydrates    | 674.12             | 684.94        |
| Non-fibrous carbohydrates | 13.60           | 49.26         |
| TDN \textsuperscript{c} | 634.48             | 469.95        |

\textsuperscript{a} NDFap: neutral detergent fiber corrected for ash and protein; \textsuperscript{b} ADFp: acid detergent fiber corrected for protein; \textsuperscript{c} TDN: total digestible nutrients.

Table 2. Percentage composition of each silage, and chemical composition at the ensiling time.

| Ingredients (%DM) | Diets |
|-------------------|-------|
|                   | SS    | SSCS  | SSBF  | SSBC  |
| Corn              | 0.0   | 29.0  | 14.5  | 14.5  |
| Soybean meal      | 0.0   | 19.3  | 19.2  | 19.6  |
| Babassu cake      | 0.0   | 0.0   | 0.0   | 14.5  |
| Babassu flour     | 0.0   | 0.0   | 14.5  | 0.0   |
| Urea              | 0.0   | 0.5   | 0.6   | 0.2   |
| Mineral salt      | 0.0   | 1.2   | 1.2   | 1.2   |
| Sugarcane         | 100.0 | 50.0  | 50.0  | 50.0  |

| Item                        | Chemical Composition (g/kg DM) |
|-----------------------------|--------------------------------|
| Dry matter (g/kg DM)        | 236.40 391.90 393.30 398.20 |
| Mineral matter              | 26.40   29.20 38.30 36.30 |
| Organic matter              | 973.60  970.80 961.70 963.70 |
| Crude protein               | 32.35 141.75 143.59 145.32 |
| NDF \textsuperscript{a}    | 675.10 583.80 604.30 611.30 |
| ADF \textsuperscript{b}    | 455.50 287.70 343.80 322.80 |
| WSC \textsuperscript{c}    | 247.6  99.04  82.00  84.56 |
| Hemicellulose              | 219.60 296.10 260.50 288.50 |
| pH \textsuperscript{d}     | 4.71   5.20  5.76  5.09 |

SS: sugarcane silage (control); SSCS: sugarcane silage with corn and soybean meal (standard diet); SSBF: sugarcane silage with corn, soybean meal, and babassu flour; SSBC: sugarcane silage with corn, soybean meal, and babassu cake; \textsuperscript{a} NDF: neutral detergent fiber; \textsuperscript{b} ADF: acid detergent fiber; \textsuperscript{c} WSC: water-soluble carbohydrates; \textsuperscript{d} pH: hydrogen potential.

2.3. Fermentative Profile

After 45 days of fermentation, the silos were opened and then weighed and sampled. The pH values were determined by analyzing samples of 25 g of each treatment and adding 100 mL of distilled water. The readings were taken after 1 h of rest, according to the methodology proposed by Bolsen et al. \cite{16}.

Ammonia nitrogen content as a percentage of total nitrogen (N-NH\textsubscript{3}/NT, in %) was determined using 15 g of fresh silage. In this sample, 100 mL of 15% potassium chloride solution was added, after which it was processed in a blender for about 10 min, filtered, and a volume of 10 mL was collected. This material was transferred into a digestion
tube containing 250 mg of calcined magnesium oxide. Later, the ammonia was captured after distillation [17]. The analysis of organic acids (lactic acid (LA), acetic acid (AA), propionic acid (PA), and butyric acid (BA)) was determined by high-precision liquid-phase chromatography (HPLC) according to the methodology described by Siegfried et al. [18]. To determine the buffer power (BP), a sample of 15 g of the material was sent for analysis, as described in [19].

Dry matter losses from silages in the form of gases and effluents were quantified by weight difference [20]. Gas losses (GL) were obtained by the equation following:

\[ GL = \frac{(WSf - WSo)}{(FMf \times DMf)} \times 100 \]

where \( GL \) = gas loss during storage (% of initial DM); \( WSf \) = weight of the silo in the silage; \( WSo \) = weight of silo at opening; \( FMf \) = forage mass in the silage; and \( DMf \) = forage DM content in the silage.

Effluent losses (EL) were calculated by the equation below, based on the difference in the weight of sand placed at the bottom of the vessel when closing and opening the experimental silos.

\[ E = \frac{(Wop - Wen)}{(GMef)} \times 1000 \]

where \( E \) = effluent production (kg/t of green mass); \( Wop \) = set weight (silo + sand + cloth + mesh) at opening (kg); \( Wen \) = set weight (silo + sand + cloth + mesh) in the silage (kg); and \( GMef \) = green mass of ensiled forage (kg).

The dry matter recovery (DMR) index was estimated using the following equation:

\[ DMR = \frac{(FMop \times DMop)}{(FMcl \times DMcl)} \times 100 \]

where \( FMop \) = forage mass at opening; \( DMop \) = DM content at opening; \( FMcl \) = forage mass at closing; and \( DMcl \) = DM content of forage at closure.

2.4. Chemical Analysis

The chemical composition of the ingredients—samples of fresh material, before ensiling, and after opening the silos—was recorded. These samples were pre-dried for 72 h in a forced ventilation oven at 60 ± 5 °C, and then milled in a knife mill (Wiley type) with a 1 mm mesh sieve.

Thereafter, the contents of the following variables were determined—dry matter (DM), by method 934.01 [21]; crude protein (CP), by method 920.87 [21]—using an apparatus developed for nitrogen determination, according to the conventional method of Kjeldahl. Digestion and distillation systems were incorporated in a single set: ether extract (EE), by method 920.39 [21] through the goldfish; mineral matter (MM), by method 930.05 [21] by burning in muffle; and neutral detergent fiber (NDF) [22] and acid detergent fiber (ADF) [23], by autoclave.

Meanwhile, organic matter (OM) content was obtained using the following equation:

\[ OM = 100 - MM \]

Moreover, NDF concentration was corrected for ash and protein (NDFap), determined by the following equation:

\[ \%NDFapDM = \%NDF - (\%NDIPDM + \%NDIADM) \]

where \( NDIP \) = neutral detergent insoluble protein; \( NDIA \) = neutral detergent insoluble ash; and \( DM \) = dry matter. Meanwhile, ADF corrected for protein (ADFp) was calculated from the subtraction from the ADF of acid detergent insoluble protein (ADIP). Additionally, lignin was determined as described by Sniffen et al. [24]; hemicellulose (HEM) content was calculated from the subtraction from the NDFp of the ADFp; and cellulose (CEL) was determined from the subtraction from the ADFp of the lignin.
Furthermore, total carbohydrates (TC) were calculated using the following equation:

$$\text{TC} = 100 - (\%\text{CP} + \%\text{MM} + \%\text{EE})$$ \[25\];

and the concentration of non-fibrous carbohydrates (NFC) was estimated by the following equation \[26\]:

$$\text{NFC} = 100 - (\%\text{PB} + \%\text{NDFap} + \text{EE} + \text{MM})$$

while total digestible nutrients (TDN) were estimated by the following equation \[27\]:

$$\text{TDN} = \left(\text{Deg} + (1.25 \times 10^6) - \text{MM}\right)$$

where Deg = Degradability; 1.25 = correction factor; EE = ether extract; and MM = mineral matter.

### 2.5. In Situ Degradability

The subsamples were collected from each silo to determine their in situ degradability. The silages were grounded using a Wiley mill with 5 mm sieves; later, 4 g of each subsample was packed in non-woven fabric (NWF) bags (13 × 4 cm), with weight (100 g/m\(^2\)) in the proportion of 15 to 20 mg of the sample per cm\(^2\) of bag area \[28\].

Three cows (Dutch/crossbred) of around 530 ± 30 kg, fistulated in the rumen, belonging to the Dairy Cattle Nutrition Research Unit of the Center for Agrarian and Environmental Sciences, were fed twice a day, at 7:00 a.m. and 5:00 p.m., with sugarcane, milled pearl millet, soybean meal, and mineral mixture. NWF bags were incubated for times of 0, 6, 24, and 72 h \[29\]. The incubations were performed in descending order so that all bags were removed and washed at the same time. The bags at time zero or soluble fraction (fraction a) were washed in a water bath at 39 °C for one hour; fraction a is the water-soluble fraction of the feed at time zero that did not pass through the rumen. All bags from different incubation times were washed together under running water until the water became clear. Later, these bags were placed in an oven with forced air circulation at 60 ± 5 °C, for 72 h, to perform the DM, CP, and NDF analysis \[21\].

Estimation of in situ degradability parameters was performed based on the models proposed by Sampaio \[30\] and Ørskov and McDonald \[31\], expressed as follows:

$$\text{PD} = A - B. e^{-c.t}$$

where PD = actual percentage of nutrient degraded after t hours of incubation in the rumen; A = maximum potential degradation of the material within the nylon bag; B = potentially degradable fraction of material kept in the nylon bag after time zero; c = degradation rate of the remaining fraction in the nylon bag after time zero; and t = incubation time.

Effective degradability (ED) is the percentage of feed that is actually degraded in the rumen, and was estimated considering passage rates of 2, 5, and 8 h, which can be attributed to increasing levels of feed intake measured in hours. These rates are simulations of the ingestion of poor-quality forage and straw or stubble, good-quality composite and forage diets, and diets of concentrated ingredients, respectively, using the equation proposed by Ørskov and McDonald \[31\]:

$$\text{ED} = a + \frac{bc}{(c + k)}$$

where ED = effective degradation; a = soluble fraction, rapidly degraded; b = insoluble fraction, slowly degraded; c = fractional rate of b degradation; and k = pass rate.

NDF degradability was estimated using the model proposed by Mertens and Loften \[32\]:

$$\text{Rt} = B. e^{-c.t} + I$$

where Rt = degradable fraction at time t; and I = non-degradable fraction.

After adjusting the NDF degradation equation, fractions were standardized using the following equations \[33\]:

$$\text{Fp} = \frac{B}{(B + I)} \times 100$$

$$\text{Ip} = \frac{I}{(B + I)} \times 100$$
where \( F_p \) = standardized potentially degradable fraction (%); \( I_p \) = standardized non-degradable fraction (%); and \( B, I \) = as defined before.

The colonization time (lag time) corresponds to the time between the beginning of incubation and the microbial action. It was calculated according to the model proposed by Ørskov and McDonald [31]:

\[
\ln(RPD_{t_0} - \ln RPD_t)/c
\]

where \( \ln RPD_{t_0} \) = natural logarithm of the potentially degradable residue at time 0 h; \( RPD_t \) = natural logarithm of potentially degradable residue in the last incubation time used; and \( c \) = rate of degradation of fraction.

The in situ degradability assay was conducted in a randomized complete block design with a split-plot arrangement and four treatments. The treatments consisted of SS: sugarcane silage (control); SSCS: sugarcane silage with corn and soybean meal; SSBF: sugarcane silage with corn, soybean meal, and babassu mesocarp flour; and SSBC: sugarcane silage with corn, soybean meal, and babassu cake. In the experimental design, blocks, plots, and subplots were represented by the cows, treatments, and incubation times (0, 6, 24, and 72 h), respectively.

2.6. Statistical Analysis

Two samples were obtained from replications of treatments. The parametric assumptions presented values within the normality of particles and homogeneity of variables. ANOVA was performed, and the results were presented as a test of means.

The degradation was evaluated by the analysis of variance (ANOVA) to compare the means (SAS PROC MEANS) (SAS, 2002). The parameters \( a, b, \) and \( c \) and the in situ degradation curves of the nutritional factors were obtained according to the exponential equation, as proposed by [31], using the procedure for nonlinear models (PROC NLIN) of SAS (2002).

The means of DM, CP, and NDF degradation data for each incubation time, along with data referring to the fermentative profiles, bromatological composition, and silage losses, were compared using Tukey’s test at the 5% probability level. The analysis was performed using the procedure “Mixed” (SAS, 2002).

3. Results

The highest pH values were observed for SSCS and SSBF, and the lowest value for SS (\( p < 0.0001 \)). SS silage showed higher GL and EL values when compared to all TMRSs (\( p < 0.0001 \)). All TMRSs presented higher DMR values than SS (\( p < 0.0001 \)) (Table 3).

Table 3. Values of pH, buffering power (BP), gas losses (GL), effluent losses (EL), and dry matter recovery (DMR) of total mixed ration silages with babassu byproducts.

| Variables       | Treatments   | SEM  | \( p \)-Value |
|-----------------|--------------|------|--------------|
|                 | SS           | SSCS | SSBF         | SSBC         |
| pH              | 3.44 \( a \) | 4.06 \( b \) | 4.08 \( a \) | 4.01 \( b \) | 0.010 | 0.0001 |
| WSC (g/kg DM)   | 122.6 \( a \) | 86.0 \( b \) | 75.6 \( b \) | 73.3 \( b \) | 7.272 | 0.0023 |
| N-NH\(_3\) (%N) | 0.59 \( a \)  | 10.11 \( b \) | 3.47 \( a \) | 8.27 \( b \) | 0.287 | 0.0001 |
| BP (E. mgNaOH)  | 0.05         | 0.05 | 0.04         | 0.05         | 0.002 | 0.0724 |
| GL (%DM)        | 0.29 \( a \) | 0.11 \( b \) | 0.07 \( a \) | 0.07 \( b \) | 0.019 | 0.0001 |
| EL (kg/ton)     | 48.15 \( a \) | 22.48 \( b \) | 21.44 \( b \) | 21.11 \( b \) | 2.655 | 0.0001 |
| DMR (%DM)       | 73.37 \( b \) | 83.74 \( a \) | 82.08 \( a \) | 83.92 \( a \) | 1.144 | 0.0001 |

SS: sugarcane silage (control); SSCS: sugarcane silage with corn and soybean meal (standard diet); SSBF: sugarcane silage with corn, soybean meal, and babassu flour; SSBC: sugarcane silage with corn, soybean meal, and babassu cake; WSC: water-soluble carbohydrates; BP: buffer power; GL: gas losses; EL: effluent losses; DMR: dry matter recovery. Means followed by equal letters in the lines do not differ significantly according to Tukey’s test at 5% probability. SEM: standard error of the mean.

SSCS had the highest contents of N-NH\(_3\) (\( p < 0.0001 \)) (Table 4). The SS treatment exhibited greater values of LA, BA, and ethanol compared to all TMRSs (\( p < 0.0001 \)).
AA values in SS and SSCS were similar, and showed higher values than those of SSBF and SSBC \( (p < 0.0001) \).

**Table 4.** Values of lactic acid (LA), acetic acid (AA), propionic acid (PA), butyric acid (BA), and ethanol from total feed silages with babassu byproducts.

| Variables | Treatments | SEM | \( p \)-Value |
|-----------|------------|-----|--------------|
| LA (% DM) | SS 6.53 \textsuperscript{a} | SSSC 3.72 \textsuperscript{b} | SSBF 2.61 \textsuperscript{c} | SSBC 3.56 \textsuperscript{b} | 0.107 | <0.0001 |
| AA (% DM) | SS 0.74 \textsuperscript{a} | SSSC 0.76 \textsuperscript{a} | SSBF 0.62 \textsuperscript{b} | SSBC 0.57 \textsuperscript{b} | 0.021 | <0.0001 |
| PA (% DM) | SS 0.10 \textsuperscript{b} | SSSC 0.09 \textsuperscript{bc} | SSBF 0.08 \textsuperscript{c} | SSBC 0.15 \textsuperscript{a} | 0.005 | <0.0001 |
| BA (% DM) | SS 0.07 \textsuperscript{a} | SSSC 0.03 \textsuperscript{b} | SSBF 0.03 \textsuperscript{b} | SSBC 0.03 \textsuperscript{b} | 0.001 | <0.0001 |
| Ethanol (% DM) | SS 8.10 \textsuperscript{a} | SSSC 3.02 \textsuperscript{c} | SSBF 3.20 \textsuperscript{c} | SSBC 3.78 \textsuperscript{b} | 0.104 | <0.0001 |

LA: lactic acid; AA: acetic acid; BA: butyric acid; PA: propionic acid; SS: sugarcane silage (control); SSCS: sugarcane silage with corn and soybean meal (standard diet); SSBF: sugarcane silage with corn, soybean meal, and babassu flour; SSBC: sugarcane silage with corn, soybean meal, and babassu cake. Means followed by equal letters in the lines do not differ significantly according to Tukey’s test at 5% probability. SEM: standard error of the mean.

In the chemical composition analysis, all TMRSs presented higher values of DM, CP, NFC, and TDN than the SS treatment \( (p < 0.0001) \) (Table 5). In contrast, SS showed higher values of NDFap, ADFp, LIG, and CEL than all TMRSs \( (p < 0.0001) \) (Table 5). The SSBF and SS had higher values of HEM compared to SSSC \( (p = 0.0019) \).

**Table 5.** Chemical composition of total feed silages with babassu byproducts.

| Variables (g/kg DM) | Treatments | SEM | \( p \)-Value |
|---------------------|------------|-----|--------------|
| DM                  | SS 169.39 \textsuperscript{b} | SSSC 349.07 \textsuperscript{a} | SSBF 344.39 \textsuperscript{a} | SSBC 352.32 \textsuperscript{a} | 3.26 | <0.0001 |
| MM                  | SS 45.63 \textsuperscript{a} | SSSC 35.75 \textsuperscript{a} | SSBF 41.85 \textsuperscript{a} | SSBC 40.15 \textsuperscript{a} | 2.51 | 0.0837 |
| OM                  | SS 954.37 \textsuperscript{a} | SSSC 964.25 \textsuperscript{a} | SSBF 958.15 \textsuperscript{a} | SSBC 999.85 \textsuperscript{a} | 2.51 | 0.0837 |
| CP                  | SS 23.33 \textsuperscript{b} | SSSC 151.19 \textsuperscript{a} | SSBF 136.98 \textsuperscript{a} | SSBC 142.14 \textsuperscript{a} | 4.03 | <0.0001 |
| NDFap               | SS 724.49 \textsuperscript{a} | SSSC 354.84 \textsuperscript{c} | SSBF 455.09 \textsuperscript{b} | SSBC 433.96 \textsuperscript{b} | 6.00 | <0.0001 |
| ADFp                | SS 647.0 \textsuperscript{a} | SSSC 330.74 \textsuperscript{a} | SSBF 360.31 \textsuperscript{b} | SSBC 393.16 \textsuperscript{b} | 10.25 | <0.0001 |
| LIG                 | SS 111.66 \textsuperscript{a} | SSSC 55.04 \textsuperscript{b} | SSBF 70.90 \textsuperscript{b} | SSBC 73.16 \textsuperscript{b} | 4.70 | <0.0001 |
| CEL                 | SS 535.41 \textsuperscript{a} | SSSC 275.70 \textsuperscript{a} | SSBF 289.41 \textsuperscript{b} | SSBC 320.00 \textsuperscript{b} | 11.77 | <0.0001 |
| HEM                 | SS 77.42 \textsuperscript{ab} | SSSC 24.10 \textsuperscript{c} | SSBF 94.78 \textsuperscript{a} | SSBC 40.80 \textsuperscript{b} | 11.58 | 0.0019 |
| EE                  | SS 13.12 \textsuperscript{a} | SSSC 13.52 \textsuperscript{a} | SSBF 12.68 \textsuperscript{a} | SSBC 12.46 \textsuperscript{b} | 1.01 | 0.8827 |
| NFC                 | SS 193.43 \textsuperscript{c} | SSSC 444.70 \textsuperscript{a} | SSBF 353.40 \textsuperscript{b} | SSBC 371.20 \textsuperscript{b} | 7.67 | <0.0001 |
| TDN                 | SS 402.67 \textsuperscript{c} | SSSC 583.15 \textsuperscript{a} | SSBF 520.50 \textsuperscript{b} | SSBC 516.83 \textsuperscript{b} | 2.90 | <0.0001 |

SS: sugarcane silage (control); SSCS: sugarcane silage with corn and soybean meal (standard diet); SSBF: sugarcane silage with corn, soybean meal, and babassu flour; SSBC: sugarcane silage with corn, soybean meal, and babassu cake; DM: dry matter; MM: mineral matter; OM: organic matter; CP: crude protein; NDFap: neutral detergent fiber corrected for ash and protein; ADFp: acid detergent fiber corrected for protein; LIG: lignin; CEL: cellulose; HEM: hemicellulose; EE: ether extract; NFC: non-fibrous carbohydrates; TDN: total digestible nutrients; SEM: standard error of the mean. Means followed by equal letters in the lines do not differ significantly according to Tukey’s test at 5% probability.

All TMRSs showed higher percentages of fraction \( a \) when compared with SS. The TMRSs presented higher percentages of DM in fraction \( b \). When considering fraction \( c \), SSSC presented a lower value than SS, SSBF, and SSBC, which showed similar values (Table 6).

Succino showed the highest values of PD and ED of DM as a result of the characteristics of fractions \( a, b, \) and \( c \) (Table 6). All TMRSs presented higher values of CP degradation parameters for the \( a \) and \( b \) fractions compared to SS (Table 6). However, fraction \( c \) exhibited a higher value for SS, followed by SSSC, and lower values for SSBC and SSBF.

The results also showed that SS had the highest lag time (Table 7) compared to the TMRSs. SSBF showed a higher percentage of Fp and, consequently, a lower Ip fraction.
### Table 6. In situ degradability of dry matter (DM) and crude protein (CP) of total feed silages with babassu byproducts.

| Items                      | Treatments |
|----------------------------|------------|
|                            | SS         | SSCS        | SSBF        | SSBC        |
| **In Situ Degradability of DM** |            |             |             |             |
| a (%)                      | 25.56      | 33.41       | 30.31       | 34.23       |
| b (%)                      | 23.08      | 54.56       | 36.87       | 26.25       |
| c (%/hour)                 | 3.82       | 2.02        | 3.56        | 3.75        |
| PD (%)                     | 46.83      | 74.16       | 63.84       | 58.37       |
| ED 2 (%/hour)              | 40.71      | 60.83       | 53.92       | 51.35       |
| 5 (%/hour)                 | 35.56      | 49.11       | 45.64       | 45.48       |
| 8 (%/hour)                 | 33.02      | 44.41       | 41.66       | 42.61       |
| R²                         | 0.9305     | 0.5924      | 0.6617      | 0.3460      |
| **In Situ Degradability of CP** |            |             |             |             |
| a (%)                      | 20.17      | 34.05       | 26.27       | 30.65       |
| b (%)                      | 20.32      | 90.15       | 86.44       | 33.81       |
| c (%/hour)                 | 3.67       | 1.00        | 1.00        | 3.34        |
| PD (%)                     | 39.47      | 79.68       | 62.62       | 61.37       |
| ED 2 (%/hour)              | 33.32      | 63.55       | 50.81       | 51.80       |
| 5 (%/hour)                 | 28.77      | 48.74       | 38.10       | 44.19       |
| 8 (%/hour)                 | 26.56      | 43.83       | 34.07       | 40.61       |
| R²                         | 0.7511     | 0.8801      | 0.4832      | 0.8128      |

SS: sugarcane silage (control); SSCS: sugarcane silage with corn and soybean meal (standard diet); SSBF: sugarcane silage with corn, soybean meal, and babassu flour; SSBC: sugarcane silage with corn, soybean meal, and babassu cake; DM: dry matter; CP: crude protein; a = water-soluble fraction (%); b = water-insoluble but potentially degradable fraction (%); c = fraction b degradation rate (%/h); PD = potential degradation over 72 h; ED = effective degradation.

### Table 7. Colonization time (Lag time), standardized potentially degradable fraction (Fp), standardized non-degradable fraction (Ip), passage rate (k), and coefficient of determination for NDF of total feed silages (TFSs) with babassu byproducts.

| Items                      | Treatments |
|----------------------------|------------|
|                            | SS         | SSCS        | SSBF        | SSBC        |
| **Lag time (hours)**       | 5.57       | 3.77        | 2.28        | 2.80        |
| Fp (%)                     | 40.96      | 42.00       | 50.86       | 46.33       |
| Ip (%)                     | 59.04      | 58.00       | 49.14       | 53.67       |
| k (%/hour)                 | 3.49       | 2.13        | 2.46        | 1.26        |
| R²                         | 0.9978     | 0.9969      | 0.9967      | 0.9984      |

Lag time: colonization time; Fp: standardized potentially degradable fraction; Ip: standardized non-degradable fraction; k: ticket fee; R²: coefficient of determination; SS: sugarcane silage (control); SSCS: sugarcane silage with corn and soybean meal (standard diet); SSBF: sugarcane silage with corn, soybean meal, and babassu flour; SSBC: sugarcane silage with corn, soybean meal, and babassu cake.

There was an interaction between incubation time and silages ($p < 0.05$) for DM, CP, and NDF degradation, as shown in Table 8. All TMRSs had higher DM degradation when compared to SS at all incubation times. At 24 h, the SSCS, SSBF, and SSBC did not differ from one another, and all had higher DM degradation than SS ($p = 0.0002$). At 72 h, SSCS had the greatest DM degradation. For the interaction between incubation time and CP degradation of the silage (Table 8), it was observed that at times of 6 and 24 h, SSCS had higher degradation ($p = 0.0034$) than SS and SSBF. Likewise, at 72 h, SSCS had the greatest CP degradation.
Table 8. Time x treatment interaction for dry matter (DM), crude protein (CP), and neutral detergent fiber (NDF) degradation of total feed silages with babassu byproducts.

| Time | Treatment | SEM  | p-Value |
|------|-----------|------|---------|
|      | DM        |      |         |
| 6    | SS        | 32.57<sup>Cb</sup> | 57.99<sup>Ca</sup> | 43.75<sup>Ca</sup> | 70.25<sup>Ab</sup> | 4.40<sup>Ac</sup> | 0.0002 |
| 24   | SSCS      | 42.02<sup>Ca</sup> | 55.13<sup>Ba</sup> | 54.15<sup>Ba</sup> | 70.25<sup>Ab</sup> | 4.40<sup>Ac</sup> | 0.0002 |
| 72   | SSBF      | 38.55<sup>Ca</sup> | 55.13<sup>Ba</sup> | 54.15<sup>Ba</sup> | 64.78<sup>Ac</sup> | 4.40<sup>Ac</sup> | 0.0002 |
|      | SSBC      | 43.47<sup>Ca</sup> | 55.13<sup>Ba</sup> | 54.15<sup>Ba</sup> | 64.78<sup>Ac</sup> | 4.40<sup>Ac</sup> | 0.0002 |

| Time | Treatment | SEM  | p-Value |
|------|-----------|------|---------|
|      | CP        |      |         |
| 6    | SS        | 37.25<sup>Ab</sup> | 61.39<sup>Ab</sup> | 47.62<sup>Bb</sup> | 71.88<sup>Ab</sup> | 4.40<sup>Ac</sup> | 0.0002 |
| 24   | SSCS      | 47.79<sup>Ba</sup> | 70.25<sup>Ab</sup> | 57.29<sup>Bb</sup> | 69.57<sup>Ab</sup> | 4.40<sup>Ac</sup> | 0.0002 |
| 72   | SSBF      | 36.38<sup>Ca</sup> | 70.25<sup>Ab</sup> | 57.29<sup>Bb</sup> | 69.57<sup>Ab</sup> | 4.40<sup>Ac</sup> | 0.0002 |
|      | SSBC      | 44.63<sup>Cab</sup> | 70.25<sup>Ab</sup> | 57.29<sup>Bb</sup> | 69.57<sup>Ab</sup> | 4.40<sup>Ac</sup> | 0.0002 |

| Time | Treatment | SEM  | p-Value |
|------|-----------|------|---------|
|      | NDF       |      |         |
| 6    | SS        | 22.71<sup>Ca</sup> | 24.33<sup>Bb</sup> | 21.89<sup>Ca</sup> | 34.57<sup>Ba</sup> | 2.05<sup>Ac</sup> | 0.0029 |
| 24   | SSCS      | 22.37<sup>Ba</sup> | 24.33<sup>Bb</sup> | 21.89<sup>Ca</sup> | 34.57<sup>Ba</sup> | 2.05<sup>Ac</sup> | 0.0029 |
| 72   | SSBF      | 22.97<sup>Ca</sup> | 24.33<sup>Bb</sup> | 21.89<sup>Ca</sup> | 34.57<sup>Ba</sup> | 2.05<sup>Ac</sup> | 0.0029 |
|      | SSBC      | 29.02<sup>Bb</sup> | 24.33<sup>Bb</sup> | 21.89<sup>Ca</sup> | 34.57<sup>Ba</sup> | 2.05<sup>Ac</sup> | 0.0029 |

SS: sugarcane silage (control); SSCS: sugarcane silage with corn and soybean meal (standard diet); SSBF: sugarcane silage with corn, soybean meal, and babassu flour; SSBC: sugarcane silage with corn, soybean meal, and babassu cake. Means followed by equal letters for the same chemical constituent (DM, CP, or NDF)—lowercase in the columns—do not differ significantly according to Tukey’s test (p > 0.05). Uppercase in columns—differ significantly according to Tukey’s test (p < 0.05). SEM: standard error of the mean; Treat: treatment; Ti: incubation time; Treat × Ti: interaction between treatment and incubation time.

The results obtained indicated that the greatest NDF degradations (p = 0.0029) in each silage occurred at the time of 72 h. Meanwhile, at the time of 24 h, the degradations were intermediate, and higher than at the time of 6 h (Table 8). The SSCS and SSBC treatments showed similar NDF degradations at 6 and 24 h. Still, at 24 h, it could be observed that SS had higher NDF degradation than SSCS. However, SSCS at 72 h showed the highest NDF degradation (p = 0.0029) (Table 8).

4. Discussion

4.1. Fermentative Profile

According to [34], the ideal pH range for well-preserved silages is 3.8 to 4.2. The values found for all TMRSs presented values within the recommended range; on the other hand, SS presented an average value of 3.44, which is below the recommended range. Sugarcane has elevated levels of soluble carbohydrates—the main substrate for silage fermentation—allowing for a rapid dominance of lactic bacteria, causing a drop in pH [35,36]. The action of homofermentative lactic acid bacteria increases the concentration of lactic acid, which is largely responsible for the intense reduction in pH [37].

Soluble carbohydrates from sugarcane presented the highest value (247.6 g/kg) at the start of the silage, leading to a significant reduction in the pH of SS (pH 3.44) compared to all TMRSs (pH 4.0). Rodrigues et al. [36] pointed out that silages with pH below 3.8 are more susceptible to the occurrence of greater yeast and fungus activity, leading to ethanol fermentation and, consequently, decreasing the nutritional value of the silage and increasing dry matter losses. In the present study, SS, with the lowest pH, had higher values of lactic acid, ethanol, and losses of gases and effluents and, thus, lower dry matter recovery.

SSCS presented higher values of N-NH3 than SS, which was probably to the detriment of higher CP contents of the ingredients used in ensilage (Table 1), thus allowing a greater
extent of proteolysis in the initial phase of the fermentation process. Regarding silages composed exclusively of sugarcane, this degradation was expected to be inhibited by the rapid drop in pH. Despite the high values of N-NH₃ observed in TMRSs with babassu byproducts, they are still within the recommended range in silages (up to 10% total N), indicating quality in the fermentation process [38].

Kung Jr et al. [37] stated that excess ammonia nitrogen is a result of clostridia activity responsible for protein degradation, and can inhibit the reduction in pH with milder drops, preventing the achievement of the ideal pH of silages.

With regard to ethanol, SS showed the highest values, indicating the importance of adding concentrates with or without babassu byproducts to the silages to dilute the excess soluble carbohydrates. Rodrigues et al. [36], evaluating mixed silages with sugarcane, obtained lower ethanol production through a dilution effect when they added high amounts of DM byproducts to the ensiled mass mixtures. These authors observed higher values for ethanol, gas losses, and DM losses in sugarcane silage without additives.

The addition of babassu byproducts in the TMRSs based on sugarcane silage allowed good fermentation of the ensiled material, keeping the pH within the recommended range, and was efficient in reducing GL and EL, as these silages had lower losses compared to SS, as observed from the results obtained in this study.

The lower GL observed in all TMRSs compared to SS resulted from the adequate pH and lower ethanol fermentation in these silages. The lower effluent losses were due to the capacity of the concentrates to absorb moisture and dilute soluble sugar from the sugarcane silage. All TMRSs presented lower GL and EL and, consequently, higher DMR than SS, and it can be inferred that TMRSs with or without babassu byproducts were efficient in providing DMR above 82% DM. It has been suggested that the highest values of moisture, AA, BA, and ethanol in SS may be the main causes of the highest GL and EL [34].

Slight variations in the lactic acid bacteria populations present in different silages may be responsible for the effects on acetic acid levels. The values found in this study were satisfactory, and were consistent with the findings of McDonald et al. [34], who stated that acetic acid above 2% can demonstrate the action of enterobacteria and reduce the intake of silage by animals. It is worth highlighting that these moderate concentrations of acetic acid are a crucial factor in fermentation, since its action as an antifungal is more efficient than that of lactic acid, which is essential for the aerobic stability of silages [39]. Despite the variations in BA and PA in the silages, the values followed those recommended in the literature [39].

4.2. Chemical Composition

The highest values of DM and CP in all TMRS treatments showed the importance of the addition of concentrates and the feasibility of babassu byproducts, since they were efficient in acting as a hygroscopic source—increasing the DM—and as protein sources, increasing the CP content. All TMRSs presented lower GL and EL and, consequently, higher DMR than SS, and it can be inferred that TMRSs with or without babassu byproducts were efficient in providing DMR above 82% DM. It has been suggested that the highest values of moisture, AA, BA, and ethanol in SS may be the main causes of the highest GL and EL [34].

A lower level of NDF was observed in all TMRSs. This result is interesting due to being directly linked to the intake and digestibility of DM. According to Van Soest [40] and Mertens [41], the NDF is composed of hemicellulose and the ADF. ADF is composed of the less digestible (cellulose) and indigestible (lignin) portions of the forage cell wall by
ruminal microorganisms, which are correlated inversely with the intake and digestibility of DM.

However, were observed higher NFC levels for SSCS due to the lower NDF. The NFC levels are components of the cellular content with high and fast degradability, which according to Cabral et al. [42] present rapid, complete, and constant nutritional availability among feeds (98 to 100%). Furthermore, according to Berchielli et al. [43], the faster its degradability, the greater the digestibility of the cell wall and, consequently, the emptying of the rumen, allowing for a greater dry matter intake.

Significant differences in TDN were observed because of the NFC content present in the silages. SSBC showed the highest NFC content, followed by SSBF and SSCS.

### 4.3. In Situ Degradability

The analysis of in situ degradability of DM revealed that the higher percentages of a fraction a, verified in all TMRSs in relation to SS, were due to the lower contents of NDFap and ADFp, and the higher NFC contents, which provided high solubility of the DM.

The in situ degradability of DM in all TMRSs showed higher percentages of fraction a compared to SS. All TMRSs, due to the lower contents of NDFap and ADFp and higher NFC contents, provided greater DM degradability. Regarding fraction b of DM, the behavior was similar to that of fraction a, emphasizing SSCS, which presented superiority compared to the other silages. Concerning fraction c, all silages presented a degradation rate greater than or equal to 2%/h, which is considered to be within the ideal range (2 to 6%/h) for quality feeds [31].

The greater availability of nutrients for microbial degradation, promoted by the lower levels of NDFap, ADFp, and LIG, could explain the high potential degradation (PD) and effective degradation (ED) of DM in all of the TMRSs.

Similarly, the CP degradation revealed that fractions a and b showed higher values in SSCS, SSBF, and SSBC for the potential degradation (PD) and effective degradation (ED) of crude protein. This occurred due to the high nutrient availability for microbial degradation, since these silages presented lower contents of fibrous fraction and NDIN, and higher contents of NFC and CP [43]. Higher rates of PD and ED increase the amount of nitrogen available for the metabolism and synthesis of microbial protein, which is the most biologically valuable protein for ruminants [43].

SS presented the highest lag time, but without differences in the passage rate (k) and the Fp and Ip fractions. Considering that these variables come from the degradability of NDF, the proportions between ADF/NDF are very close, so the lack of difference between the Fp and Ip fractions and the passage rate (k), along with the lower pH of SS, may have been the cause of the highest lag time.

The superiority of SSBC in the DM and CP degradation was caused by the higher values of PD and ED, due to lower levels of fibrous fraction and higher levels of NFC. Thus, it can be inferred that the addition of concentrates promoted greater availability of nutrients contained in the DM, resulting in greater ruminal degradation of them, as confirmed by the higher content of NFC and TDN of these silages—especially for SSBC.

Moreover, when studying the interaction between incubation time and DM degradation of the silages, the lowest degradation at all investigated times was found in SS, unlike the superior values observed for SSBC. However, SSBF showed greater degradation capacity after 24 h of incubation compared to SSBC. Meanwhile, at 72 h, SSBC showed higher values than the other treatments, following the trend of potential DM degradation.

The interaction between incubation time and CP degradation of the silages followed the same behavior as the DM degradation interaction, but without significant differences between SSBF and SSCS. This was because SS had a higher NDIN content (70.20%), while SSCS had a lower value (42.09%). The greatest CP degradation at 6 and 24 h for SSCS and SSBC was due to lower fiber contents, associated with the lower NDIN values of SSCS (42.09%) and SSBC (46.05%). The higher nitrogen contents available for ruminal microorganisms may have allowed the development of cellulolytic and proteolytic bacteria.
The differences in CP degradation between treatments at 72 h were possibly the reason for the higher PP and ED of CP, higher NFC, and lower NDIN value (42.09%) observed in SSBC. Thus, SSBC presented higher values when compared to the other silages, providing adequate conditions for ruminal microorganisms.

Furthermore, in the interaction between the incubation time and the silages, higher NDF degradation was observed at 72 h. This result was attributed to the longer time that the ruminal microorganisms had to act. The highest value of NDF degradation of SSCS was related to fiber quality only at 72 h, specifically with lower lignin contents.

5. Conclusions

The inclusion of babassu byproducts in sugarcane silages in the form of total ration had a positive effect on the qualitative indicators of the silages—improving the fermentation profile and reducing losses, as well as improving the chemical composition and in situ degradability—which may be used in the diets of sheep.

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