Ciência Animal Brasileira
Brazilian Animal Science

DOI: 10.1590/1809-6891v25e-75861E

e-ISSN 1809-6891
Section: Veterinary Medicine | Research article

Increasing levels of cornmeal improve chemical and fermentation parameters of maniçoba silage

Níveis crescentes de fubá de milho melhoram parâmetros químico-bromatológicos e fermentativos da silagem de maniçoba

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Abstract: Ensiling maniçoba (*Manihot pseudoglaziovii*) is essential to preserve the nutrients of this forage plant. However, the plant moisture content may generate undesirable fermentations. The objective of this study was to evaluate the effects of different cornmeal inclusion levels (0%, 10%, 20%, and 30%) on the chemical composition and fermentation parameters of maniçoba silage, in addition to identifying the variables most affected by cornmeal. The concentrations of dry matter (DM), non-fiber carbohydrates (NFC), total digestible nutrients (TDN), and propionic acid increased with cornmeal inclusion levels ($P < 0.05$). Crude protein (CP), lignin, and butyric acid contents, as well as pH, were reduced by the additive ($P < 0.05$). Principal component analysis resulted in two main groups. Group I was formed by variables positively affected by cornmeal inclusion, namely DM, hemicellulose, NFC, and TDN. Group II contained variables that were negatively affected by cornmeal, namely CP, lignin, mineral matter, and butyric acid. Regardless of the addition of cornmeal, maniçoba silage displays an adequate chemical composition and a good fermentation profile for ruminant feeding. Dry matter and total digestible nutrients are the chemical variables most influenced by cornmeal inclusion, whereas pH and butyric acid are the fermentative parameters most affected by the moisture-absorbent additive. Including moderate levels of cornmeal in maniçoba silage is recommended to achieve the best fermentation profile and the highest concentration of digestible nutrients without mischaracterizing it as a roughage feed.

Keywords: Chemical composition; Ensilage of *Euphorbiaceae*; *Manihot pseudoglaziovii*; Organic acids; Principal components

Resumo: A ensilagem da maniçoba (*Manihot pseudoglaziovii*) é importante para preservar os nutrientes dessa planta forrageira. Todavia, o teor de umidade da planta pode gerar fermentações indesejáveis. Objetivou-se avaliar efeito de níveis de fubá de milho (0, 10, 20 e 30%) sobre a composição bromatológica e parâmetros fermentativos da silagem de maniçoba, além de identificar as variáveis

Received: April 11, 2023. Accepted: November 7, 2023. Published: January 15, 2024.

mais afetada pelo aditivo. As concentrações de matéria seca (MS), carboidratos não-fibrosos (CNF), nutrientes digestíveis totais (NDT) e ácido propiônico aumentaram em função dos níveis de fubá de milho (P<0,05). Os teores de proteína bruta (PB), lignina e ácido butírico, além do pH, foram reduzidos pelo aditivo (P<0,05). Dois grupos foram formados na análise de componentes principais. O grupo I foi formado por variáveis afetadas positivamente pela inclusão do fubá de milho: MS, hemicelulose, CNF e NDT. O grupo II foi formado por variáveis que tiveram seus valores reduzidos pela inclusão do aditivo: PB, lignina, matéria mineral e ácido butírico. A silagem de maniçoba, com ou sem fubá de milho, apresenta bom perfil fermentativo e composição bromatológica adequada para a alimentação de ruminantes. Os teores de MS e NDT são as variáveis da composição químico-bromatológica mais influenciadas pela inclusão do fubá de milho, enquanto pH e ácido butírico são as variáveis do perfil fermentativo mais afeadas pelo aditivo absorvente. Sugere-se a inclusão de níveis moderados de fubá na silagem de maniçoba para obter melhor perfil de fermentação e a maior concentração de nutrientes digestíveis, sem descaracterizar o alimento como volumoso.

Palavras-chave: Ácidos orgânicos; Componentes principais; Composição bromatológica; Ensilagem de euforbiáceas; *Manihot pseudoglaziovii*

1. Introduction

The Caatinga rangelands have been used as forage support for livestock over centuries[1]. However, the carrying capacity of these natural pastures oscillates throughout the year, drastically diminishing in the dry seasons[2]. Therefore, farmers from this region often adopt strategies to conserve forage to ensure feeding security and herd performance. Ensilaging is a technology employed for the conservation of the nutritional value of forage plants via anaerobic fermentation, achieved by rapidly removing O_2 from the environment to reduce the pH[3,4].

Maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) are the most ensiled crops because they have essential traits such as high contents of soluble carbohydrates and dry matter. These characteristics allow good fermentation processes and the maintenance of a high nutritional forage quality after ensilaging[5]. Tropical forage plants are more commonly ensiled compared to traditional crops due to lower soil fertility and tillage requirements. They are also perennial and demand less cultivation labor[6]. Maniçoba (*Manihot pseudoglaziovii*) is a species native to the Brazilian semiarid region that shows such characteristics. Belonging to the family *Euphorbiaceae*, it produces tuberous roots rich in starch and water, like other *Manihot* species, ensuring adaptability to semiarid conditions[7]. Maniçoba displays desirable features for forage plants, such as defoliation persistence when managed in fodder banks or Caatinga rangelands, besides excellent crude protein (CP) contents, varying from 140 to 200 g/kg[8].

Ensiling maniçoba is essential to guarantee forage allowance during the dry season in semiarid regions and ensure its use in animal feeding[9]. Maniçoba is a linamarin-rich plant, and hydrocyanic acid (HCN) is released when this amino acid is hydrolyzed in the rumen. However, HCN concentrations over 2.4 mg per kilogram of body weight may lead to animal intoxication or even death[10]. Ensiling maniçoba leads to a reduction of up to 65% in the

HCN content compared to the fresh plant because the fermentation processes reduce the enzymatic activity of linamarinase[9].

However, the high moisture content in maniçoba may increase undesirable fermentations and impair pH reduction[11]. In recent decades, moisture-absorbent additives such as cornmeal, wheat bran, or molasses have been successfully adopted for ensiling forage plants[3]. Absorbent additives can diminish the moisture content because of their hygroscopic potential and high dry matter content. As such, they provide a more suitable environment for lactic acid bacteria (LAB) while inhibiting secondary fermentations performed by other bacteria, fungi, and yeasts. Moreover, these additives can improve the feed value and increase the soluble carbohydrate contents since they are almost always high in energy[3,4]. In addition, studies about total mixed ration silages (TMR silages) were conducted successfully, with large proportions of concentrates mixed with the roughage[12].

Based on these premises, the objective of this study was to evaluate the chemical composition, pH reduction, and organic acid profile of maniçoba silage spiked with increasing levels of cornmeal. Moreover, we identified the most relevant variables to characterize these silages via principal component analysis.

2. Material and methods

The experiment was carried out at the Professor Ignacio Salcedo Experimental Station of the Instituto Nacional do Semiárido (INSA), located in the municipality of Campina Grande, state of Paraíba, Brazil (07°14′00″ S, 35°57′00″ W; 491 m above sea level). The climate is characterized as As′, that is, warm and humid with a rainy season in the autumn and winter[13]. The average rainfall is 503 mm annually, and the soil is classified as Solonetz[14,15].

The maniçoba forage used for the ensilage was harvested from the natural rangeland of the Caatinga, owned by INSA. Only leaves and thin stems (< 10 mm in diameter) were harvested and mowed into 2–3-cm particles using a stationary machine. The arboreal strata of this site have been managed since 2019, and the plants have already had two reproduction cycles.

The experimental design was completely randomized with six replicates, and experimental silos were made with polyethylene bags proper for ensiling. Each experimental silo had a 6-L capacity, and 5 kg of mass was compacted into the silos. Thus, the silage density was approximately 830 kg/m^3 on an as-fed basis. Treatments corresponded to increasing levels of cornmeal (0%, 10%, 20%, and 30%) mixed with the ensiled mass on an as-fed basis. Therefore, 0, 0.5, 1.0, and 1.5 kg of cornmeal were homogenized into maniçoba to compose the additive levels. At the time of harvesting, a 300-g aliquot was separated and identified for chemical analyses of maniçoba and cornmeal before ensiling (Table 1).

Table 1 Chemical composition of maniçoba (*Manihot pseudoglaziovii*) and cornmeal before ensiling.

Variable (g/kg DM)	Maniçoba	Cornmeal
Dry matter	210	880
Mineral matter	77	20
Organic matter	923	980
Neutral detergent fiber	406	131
Acid detergent fiber	246	40
Crude protein	185	100
Non-fiber carbohydrates	286	732
Ether extract.	46	40

**g/kg as-fed basis.*

The concentrations of dry matter (DM), mineral matter (MM), organic matter (OM), crude protein (CP), and ether extract (EE) were analyzed according to the AOAC[16]. The contents of neutral (NDF) and acid (ADF) detergent fiber were determined using the methodologies proposed by Van Soest et al.[17]. The NDF was analyzed without a heat-stable amylase and expressed inclusive of residual ash, protein, and ADF[17]. Non-fiber carbohydrates (NFC) were determined according to Sniffen et al.[18], using the following equation: NFC = 1000 – (NDF + CP + MM + EE). These variables were expressed in grams per kilogram (g/kg).

The silos remained sealed for 35 days, and the pH values were measured according to Bolsen et al.[19] at seven-day intervals in all silos. For this, the silos were opened, and the ensiled mass samples (25 g) were collected, followed by closing the silos immediately. After definitive opening, the material was collected to determine the silage concentrations of DM, MM, OM, NDF, ADF, CP, NFC, and EE using the methods described above. The lignin content (LIG) was analyzed using the AOAC method[16], and the total digestible nutrients were calculated using the equation TDN = [889 – (7.99 × ADF)][20]. The concentrations of hemicellulose (HEM) and cellulose (CEL) were calculated by subtracting the NDF from the ADF contents and the ADF from the LIG contents, respectively[21]. These variables were also expressed in grams per kilogram (g/kg).

Twenty-five grams (25 g) of fresh silage was weighed, diluted in 225 mL of distilled water, and homogenized in an industrial blender for 1 min to determine the concentrations of organic acids (acetic, butyric, propionic, and lactic acids). The resulting water extract was filtered through filter paper, and 100 mL of the extract was acidified with H_2SO_4 at 50%;

subsequently, the extract was filtered through fast filter paper. After filtration, 2 mL of the extract received 1 mL of 20% metaphosphoric acid solution and 0.2 mL of 1% carbolic acid solution, used as an internal standard. The samples were centrifuged for 10 min at 15,000 rpm, and the supernatant was collected in Eppendorf vials and frozen until analysis. The organic acids were detected by high-performance liquid chromatography (HPLC, Ciola and Gregory, Master CG model)[22].

Data underwent analysis of variance (ANOVA), normality tests of residues, and linear and quadratic regressions using the GLM procedure of SAS® OnDemand for Academics[23]. The pH data were analyzed with the MIXED procedure. Cornmeal inclusion level and seal time (seven-day intervals) were fixed effects, of which the latter was a repeated effect (repeated measurement in time). The variables were subjected to Pearson's linear correlation analysis using the CORR procedure, also from SAS® OnDemand for Academics. All statistical results were considered significant at the 5% error probability ($P < 0.05$).

In principal component analysis, the number of components was selected by eigenvalues using the Mardia criterion[24]. Thus, only components with eigenvalues greater than 1.0 were included in the analysis, which was performed using Statistica 8.0.

3. Results and discussion

Fresh maniçoba (Table 1) displayed lower DM and higher CP concentrations than those previously reported[25,26,10]. Using leaves and thin stems for ensiling maniçoba contributed to the high moisture and protein concentrations. Regarding the chemical composition of the ensilage, increasing cornmeal inclusion levels had significant effects on all variables assessed (Table 2).

The contents of DM, NFC, and HEM linearly increased with the cornmeal inclusion level. High-energy concentrates such as cornmeal are efficient moisture absorbents for ensiling tropical forage plants[3]. Contents of DM over 250 g/kg contribute to a good fermentation process during the seal period[27]. Cornmeal inclusion was crucial to achieving this standard since the maniçoba silage without additive had only 200 g/kg of DM. Costa et al.[4] found an increased DM content in elephant grass-butterfly pea silage, from 210 to 221 g/kg, when adding cornmeal to the ensiled mass. Concentrations of DM between 250 and 370 g/kg lead to more desirable (e.g., lactic fermentation) than undesirable fermentations (e.g., butyric fermentation)[28].

Non-fiber carbohydrates (NFC) comprise starch, saccharose, pectin, and other soluble sugars and are essential to silage fermentation because they enhance the soluble carbohydrate contents mainly degraded by lactic acid bacteria (LAB)[18]. Concentrates such as cornmeal are rich in NFC, whereas the maniçoba shoot is characterized by high concentrations of structural carbohydrates, especially cellulose and lignin[10]. Therefore, the increase in cornmeal inclusion levels combined with the reduction of maniçoba in the ensiled mass led to higher NFC and HEM concentrations.

Table 2 Chemical composition of maniçoba silage (*Manihot pseudoglaziovii*) with increasing cornmeal inclusion levels.

Variable (g/kg)	Cornmeal level (% as fed)				Regression equation	R^2	P-value		CV (%)
	0	10	20	30			L	Q	
DM	200	258	322	372	$\hat{Y} = 200 + 6.37x$	0.99	<0.001	0.421	1.51
MM	113	86	60	61	$\hat{Y} = 113 - 3.80x + 0.065x^2$	0.91	<0.001	0.002	4.72
OM	886	913	940	939	$\hat{Y} = 886 + 3.80x - 0.065x^2$	0.92	<0.001	0.002	0.75
NDF	433	366	309	258	$\hat{Y} = 433 - 6.99x$	0.99	<0.001	0.093	1.20
ADF	316	237	185	143	$\hat{Y} = 316 - 8.65x$	0.98	<0.001	0.098	3.86
HEM	59	63	71	73	$\hat{Y} = 59 + 0.52x$	0.82	<0.001	0.839	3.99
CEL	278	244	225	212	$\hat{Y} = 278 - 3.90x$	0.92	0.002	0.231	3.33
LIG	181	153	132	122	$\hat{Y} = 181 - 3.27x$	0.99	<0.001	0.100	0.68
CP	176	156	136	128	$\hat{Y} = 176 - 2.50x$	0.96	0.001	0.131	2.65
NFC	187	302	396	446	$\hat{Y} = 187 + 13.64x$	0.99	<0.001	0.213	2.44
EE	67	56	53	51	$\hat{Y} = 67 - 1.21x + 0.029x^2$	0.89	<0.001	<0.001	2.63
TDN	636	700	741	774	$\hat{Y} = 636 + 6.91x - 0.078x^2$	0.98	0.001	0.001	0.95

DM = dry matter. MM = mineral matter. OM = organic matter. NDF = neutral detergent fiber. ADF = acid detergent fiber. HEM = hemicellulose. CEL = cellulose. LIG = lignin. CP = crude protein. NFC = non-fiber carbohydrates. EE = ether extract. TDN = total digestible nutrients for beef cattle. x = cornmeal level. R^2 = coefficient of determination. L and Q indicate linear and quadratic effects of regression, respectively, at the 5% error probability ($p < 0.05$). CV = coefficient of variation.

A negative quadratic effect was found in the MM content, which decreased up to a cornmeal inclusion level of 20%, followed by an increase when 30% was added. A minimum MM content of 57 g/kg was reached at 29.3% cornmeal inclusion. The opposite occurred for the OM content, which increased to 20%, diminishing at a cornmeal inclusion level of 30%. A peak OM concentration of 941 g/kg was found with 29.3% cornmeal in the ensiled mass. The fresh maniçoba displayed higher MM values than cornmeal (Table 1), which explains the results, considering that the proportion of maniçoba was reduced as that of cornmeal was increased. High-energy concentrates are often poor in minerals but rich in OM[29].

The maniçoba silage concentrations of NDF, ADF, CEL, LIG, and CP linearly decreased ($P < 0.05$) with increasing cornmeal inclusion levels (Table 2). Plants native to the Brazilian semiarid region, such as maniçoba, are rich in fiber fractions, mainly cellulose and lignin, and often have unique CP contents. However, a significant part of this protein may be bound to lignin or tannins, creating complexes that diminish dry matter digestibility[30]. In the present study, the TDN concentration was elevated by increasing cornmeal levels because the proportion of maniçoba was reduced in the ensiled mass, which explains the lower EE content (Table 2). Santos et al.[31] found elevated lignin concentrations (131 g/kg DM) in maniçoba hay used to feed Santa Inês sheep and attributed the reduction in apparent digestibility to the high percentage of maniçoba in the diet.

According to the chemical composition, adding too much cornmeal to the ensiled mass may mischaracterize the maniçoba silage as a roughage feed, considering that the additive linearly reduces the NDF concentration. Thus, the NDF would keep reducing if exaggerated cornmeal levels (e.g., over 30%) were included in the ensiled mass.

Silages made with other forage plants have also been improved by cornmeal as an absorbent additive. Costa et al.[32] added cornmeal to silages composed of elephant grass genotypes (*Cenchrus purpureus* Schum.) and the butterfly pea legume (*Clitoria ternatea* L.). The authors found increased levels of DM (from 210 to 221 g/kg) and the remaining water-soluble carbohydrates (14 to 26 g/kg) when comparing the silage with or without cornmeal.

Isolated effects of cornmeal level (Table 3) and seal time (Fig. 1) were observed on the pH values ($P < 0.05$), but no interaction was found ($P = 0.231$). The pH was reduced under a quadratic effect by increasing cornmeal levels at 7, 14, 21, and 28 seal days. At 35 days, the decrease showed a linear behavior in response to increasing cornmeal levels. The pH is a key parameter for indicating good fermentation processes, characterized by more lactic than acetic, propionic, and butyric fermentations[6].

Table 3 **Hydrogen potential (pH) in maniçoba silage (*Manihot pseudoglaziovii*) spiked with increasing levels of cornmeal, evaluated for different seal times (days).**

Seal time (days)	Cornmeal level (% as fed)				Regression equation	R^2	P-value		CV (%)
	0	10	20	30			L	Q	
7	4.21	4.07	4.03	4.00	$\hat{Y} = 4.20 - 0.0145x + 0.0003x^2$	0.81	<0.001	0.005	1.01
14	4.19	4.05	3.98	3.97	$\hat{Y} = 4.18 - 0.0148x + 0.0003x^2$	0.97	<0.001	<0.001	0.35
21	4.15	4.00	3.97	3.94	$\hat{Y} = 4.14 - 0.0150x + 0.0003x^2$	0.90	<0.001	<0.001	0.66
28	4.07	3.96	3.90	3.89	$\hat{Y} = 4.07 - 0.0133x + 0.0003x^2$	0.89	<0.001	0.002	0.68
35	4.00	3.93	3.86	3.81	$\hat{Y} = 4.00 - 0.0079x$	0.98	<0.001	0.370	0.74

x = cornmeal level. R^2 = coefficient of determination. L and Q indicate linear and quadratic effects of regression, respectively, at the 5% error probability ($p < 0.05$). CV = coefficient of variation.

Cornmeal likely improved the fermentation coefficient of the ensiled mass since high-energy concentrates often have a lower buffering capacity than roughage feeds[3]. However, the pH observed in all silages remained below the acceptable values[6], varying from 3.81 to 4.21. Progressive reductions in pH values were observed in the maniçoba silage ($P < 0.05$) during the seal period (Fig. 1), with values of 4.08, 4.05, 4.02, 3.96, and 3.90 at 7, 14, 21, 28, and 35 days, respectively. The pH decrease indicates a good fermentation process in all silages[28], likely because maniçoba is a C4 plant with a lower buffering capacity than other forage plants (e.g., forage legumes)[26,32,33].

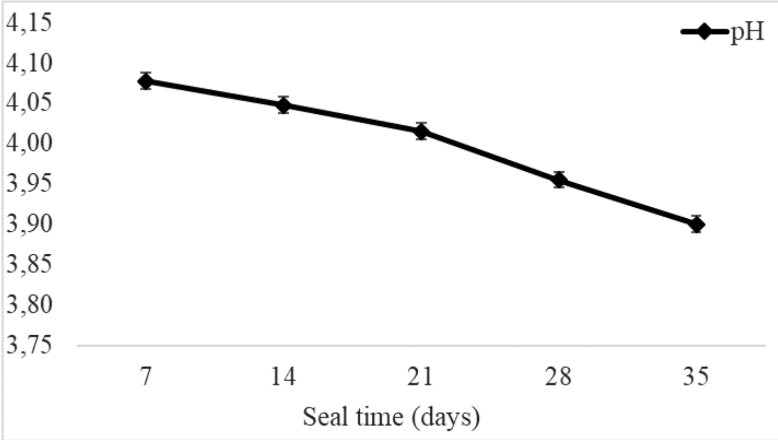

Figure 1 **Hydrogen potential (pH) in maniçoba silage (*Manihot pseudoglaziovii*) with and without the addition of cornmeal, evaluated weekly over 35 days (repeated measurement over time). Means followed by the same letter do not differ according to the probability of difference ("pdiff") adjusted to Tukey's test ($p < 0.005$). SEM = standard error of the mean.**

The concentrations of lactic and acetic acids were not affected by the increasing levels of cornmeal in the maniçoba silage (Table 4). The proportion of lactic acid was considerably higher than those of the other acids in all tested silages, suggesting good fermentation processes, including in the control treatment[4]. The contents of propionic and butyric acids and the acetic-to-propionic ratio (AA/PA) were changed with increasing cornmeal inclusion levels. The propionic acid concentration and AA/PA linearly increased with higher cornmeal levels. Conversely, the butyric acid level was reduced under a quadratic effect.

These changes in the organic acid profile by adding increasing levels of cornmeal into the ensiled mass occurred due to modifications in the roughage-to-concentrate ratio inside the silos. Diets with high percentages of high-energy concentrates, such as cornmeal, favor the proliferation of amylolytic bacteria plus the production of lactic and propionic acids. In contrast, roughage feeds such as maniçoba facilitate the proliferation of cellulolytic bacteria and acetic acid production[34].

Table 4 **Organic acids in maniçoba silage (*Manihot pseudoglaziovii*) spiked with increasing levels of cornmeal.**

Organic acid (g/kg)	Cornmeal level (% as fed)				Regression equation	R^2	P-value		CV (%)
	0	10	20	30			L	Q	
Lactic	4.934	4.707	4.612	4.588	$\hat{Y} = 4.710$	0.02	0.497	0.784	19.0
Acetic	0.209	0.181	0.172	0.166	$\hat{Y} = 0.182$	0.11	0.406	0.689	21.1
Propionic	0.068	0.075	0.085	0.090	$\hat{Y} = 0.068 + 0.0009x$	0.38	0.002	0.828	14.8
Butyric	0.479	0.072	0.018	0.000	$\hat{Y} = 0.479 – 0.0440x + 0.0009x^2$	0.96	<0.001	<0.001	27.2
AA/PA	3.07	2.41	2.02	1.84	$\hat{Y} = 3.07 – 0.077x$	0.44	0.001	0.304	24.3

*x = cornmeal level. R^2 = coefficient of determination. * or ** indicate a significant linear or quadratic regression effect, respectively, at the 5% error probability ($p < 0.05$). AA/PA = acetic-to-propionic ratio in silages. CV = coefficient of variation.*

Butyric acid production stopped at a cornmeal inclusion level of 30%, whereas a higher butyric acid level was found in the control treatment (Table 4). The population of *Clostridium* spp. was probably suppressed when cornmeal was added to the ensiled mass. This bacterial genus is sensitive to environments with pH values below 4.5, mainly when the pH decreases sharply. These results are interesting since *Clostridium* spp. are potentially toxic bacteria[35], highlighting the beneficial effect of cornmeal addition (Table 3). Backes et al.[36] also observed a linear reduction in butyric acid contents when adding cornmeal to maniçoba ensiled mass.

Significant effects were observed on all correlations between chemical composition, pH, and organic acids. Negative correlations were found between DM, pH, and butyric acid (Table 5). As mentioned, moisture reductions in the ensiled mass diminish the pH values and impede undesirable fermentations, such as butyric acid fermentation[3]. Conversely, the CP content was positively associated with butyric acid fermentation, likely because silages with high protein contents favor the activity of *Clostridium* spp., producing butyrate. At the same time, these bacteria contribute considerably to proteolysis during the fermentation process[37].

Furthermore, a negative correlation was registered between CP and propionic acid, which indicates that the dietary protein in the silages was rather derived from maniçoba than from cornmeal. Therefore, silages with high proportions of maniçoba in the ensiled mass (e.g., control silage or the silage spiked with 10% cornmeal) had low propionate contents, besides high acetic-to-propionic rates and CP contents[34].

Table 5 Pearson's linear correlation coefficients between chemical composition, pH, and organic acids in maniçoba silage (*Manihot pseudoglaziovii*) spiked with increasing levels of cornmeal.

	pH	Lactic acid	Acetic acid	Propionic acid	Butyric acid
DM	-0.93	-0.14	-0.32	0.61	-0.86
P-value	<0.001	0.513	0.120	0.002	<0.001
CP	0.89	0.10	0.30	-0.60	0.88
P-value	<0.001	0.637	0.156	0.002	<0.001
NDF	0.93	0.15	0.33	-0.62	0.88
P-value	<0.001	0.468	0.104	0.001	<0.001
ADF	0.94	0.15	0.33	-0.59	0.94
P-value	<0.001	0.470	0.104	0.002	<0.001
NFC	-0.92	-0.15	-0.35	0.62	-0.91
P-value	<0.001	0.482	0.096	0.001	<0.001
HEM	-0.85	-0.18	-0.422	0.57	-0.73
P-value	<0.001	0.400	0.004	0.003	<0.001
CEL	0.90	0.21	0.41	-0.55	0.91
P-value	<0.001	0.324	0.047	0.005	<0.001
LIG	0.93	0.16	0.34	-0.60	0.93
P-value	<0.001	0.464	0.108	0.001	<0.001

DM = dry matter. NDF = neutral detergent fiber. ADF = acid detergent fiber. HEM = hemicellulose. CEL = cellulose. LIG = lignin. CP = crude protein. NFC = non-fiber carbohydrates. pH = hydrogen potential. Lactic, acetic, propionic, and butyric acids are organic acids.

The levels of NDF, ADF, CEL, and LIG displayed high degrees of association with pH and butyric acid (Table 5). The fiber fractions were higher at lower cornmeal inclusion levels. Thus, the silages with little or no additive had more fiber fractions and moisture contents, making them more susceptible to secondary fermentations (e.g., butyric fermentation), plus less marked pH reductions[6,35]. Moreover, negative correlations were observed between NDF, ADF, and CEL with propionic acid since fibrolytic bacteria ferment acetic acid rather than propionic acid[34].

The opposite was observed for the NFC, with negative correlations with pH and butyric acid (Table 5). The starch contained in the cornmeal is one of the main components of NFC, contributing positively to lactic and propionic acid fermentation[3,18,35]. Thus, silages with higher additive inclusions showed higher NFC contents, lower pH values, and less pronounced butyric acid fermentation than those with less or no cornmeal addition.

Principal component analysis (PCA) revealed that 86.59% of the total variation could be explained by the first two PCs, with 80.29% related to PC1 and 6.30% to PC2 (Fig. 2). All variables of Group I (MM, CP, fiber fractions, EE, pH, and butyric acid) were substantially reduced by increasing cornmeal levels. In contrast, variables of Group II (DM, OM, NFC, HEM, and TDN) displayed increasing values when the additive was progressively added. The formation of two well-defined groups indicates the beneficial effects of adding cornmeal into the ensiled mass, both in terms of chemical variables and fermentation parameters[4,28,35], even though the control treatment (maniçoba with no additive) showed adequate parameters.

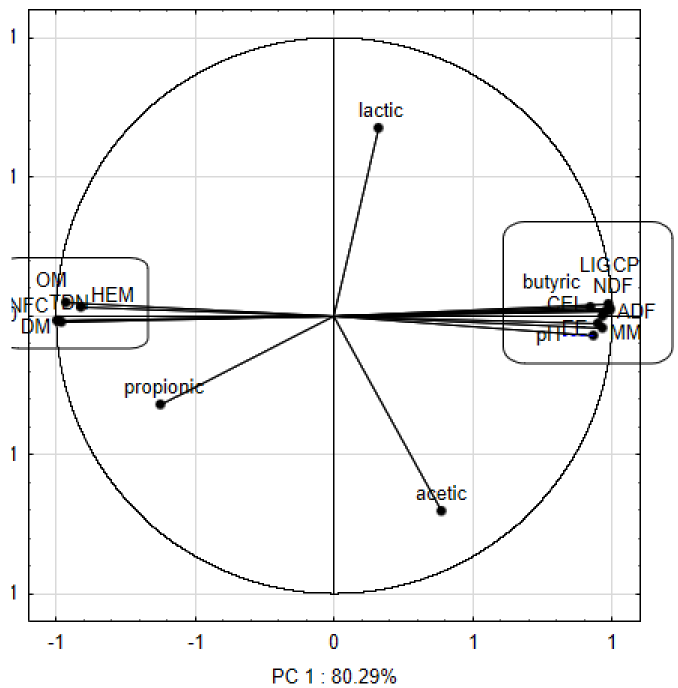

Figure 2 Distribution of variables of chemical composition, pH, and organic acids on the coordinate systems under principal components 1 and 2 (PC1 and PC2, respectively), besides Fischer grouping (Groups 1 and 2). DM = dry matter. MM = mineral matter. OM = organic matter. CP = crude protein. EE = ether extract. NDF = neutral detergent fiber. ADF = acid detergent fiber. NFC = non-fiber carbohydrates. HEM = hemicellulose. CEL = cellulose. LIG = lignin. Lactic, acetic, butyric, and propionic are organic acids.

Regardless of the addition of cornmeal, maniçoba silage showed adequate chemical composition and a good fermentation profile for ruminant feeding and nutrition. Increasing levels of cornmeal improve the organic acid profile of maniçoba silage, and a cornmeal inclusion level of 30% stopped the production of butyric acid. Dry matter and total digestible nutrients were the chemical variables most influenced by cornmeal inclusion, whereas pH and butyric acid were the fermentative parameters most affected by cornmeal.

4. Conclusion

Including moderate levels of cornmeal in maniçoba silage is recommended to achieve the best fermentation profile and the highest concentration of digestible nutrients without mischaracterizing it as a roughage feed.

Conflicts of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization: R.S., Neves, G.R., Medeiros, and J.H.S., Costa. *Formal Analysis*: P.H.F., Silva and N.L., Ribeiro. *Funding acquisition*: G.R., Medeiros. *Investigation*: P.H.F., Silva, R.S., Neves, and J.H.S., Costa. *Project administration and Supervision*: G.R., Medeiros. *Validation*: P.H.F., Silva and N.L., Ribeiro. *Visualization*: C.B.M., Carvalho, I.T.R., Cavalcante, and S.G.C.G, Santos. *Writing (original draft)*: P.H.F., Silva, R.S., Neves, J.H.S., Costa, C.B.M., Carvalho, I.T.R., Cavalcante, and S.G.C.G, Santos. *Writing (review and editing)*: P.H.F., Silva, R.S., Neves, G.R., Medeiros, J.H.S., Costa, C.B.M., Carvalho, I.T.R., Cavalcante, and S.G.C.G, Santos.

Acknowledgments

The present study was carried out with the support of the National Council for Scientific and Technological Development (CNPq).

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