

Article

Detoxified Castor Bean Meal as a Protein Supplement in Sugarcane Silage for Sheep: Intake, Digestibility, and Performance

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Abstract

Castor (*Ricinus communis*) is a toxic seed used to extract oil for the chemical industry, with castor meal as a by-product. A recently developed industrial method allows its detoxification, enabling its use as a protein-rich feed for ruminants. This study evaluated the safety of detoxified castor meal based on intake, digestibility, and performance of sheep fed sugarcane silage containing increasing levels of this ingredient. The detoxified castor meal, supplied by an oil extraction industry, underwent no additional detoxification treatment. Twenty-four intact male sheep were randomly assigned to diets containing 0%, 10%, 20% or 40% fresh matter castor meal in sugarcane silage. Diets were balanced with soybean meal and ground corn. After 60 days of feeding, no signs of intoxication were observed. Crude protein (CP) intake decreased from 0.157 to 0.128 kg/day ($p = 0.03$) and ether extract (EE) intake from 0.068 to 0.044 kg/day ($p = 0.04$). Crude protein digestibility declined from 754 to 473 g/kg ($p < 0.01$), and EE digestibility from 813 to 725 g/kg ($p = 0.02$). All other intake, digestibility, and performance variables were not significantly affected ($p \geq 0.05$). Industrially detoxified castor meal was shown to be a safe additive in sugarcane silage up to 40% by fresh matter, with no adverse effects on sheep performance.



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1. Introduction

Castor oil (*Ricinus communis*) is a versatile molecule used in the chemical industry, with castor meal as its main by-product. Despite its high CP content, castor meal has not been widely used in animal feed due to the presence of ricin, a highly toxic protein. Its main use has been as an organic fertilizer to suppress plant parasitic nematodes [1,2].

Ricin is heat sensitive, and the industrial oil extraction process reduces its activity by exposing the material to high temperature, shear, and alkalinity, particularly during solvent evaporation [3]. Although complete detoxification is not guaranteed, rumen microorganisms can degrade ricin [4], allowing its use in ruminant diets without additional detoxification [5]. Some active ricin remains, so castor meal is safe only for ruminants, not monogastrics [3]. In goats, a humoral immune response against ricin has been observed, without significant effects on metabolism or reproductive behavior [6].

Furthermore, it has been experimentally validated by our research group that supplementing sugarcane silage with detoxified castor bean meal at levels up to 40% fresh matter, the highest dose tested in this study, does not cause deleterious changes in blood parameters or in the histological structure of the rumen, liver, and kidneys of sheep. These findings confirm that the inclusion of such high levels is safe for confined sheep, representing a significant advancement over previous literature that suggested safety limits around 21% in a fresh matter diet [7].

Castor meal is a promising additive for sugarcane silage, providing nutritional and sustainable benefits [8–10]. However, its use is limited by ricin content, which can reach 5% of the seed weight [11]. Small ruminants tolerate up to 150 g/kg dry matter (DM) of non-detoxified meal [6], partly due to high ruminal proteolytic activity that degrades ricin [4]. Physical and chemical detoxification is necessary to ensure nutritional quality and feed safety [12].

High sugar content in sugarcane silage promotes fermentation, lactic acid bacteria populations [13], and rapid acidification, but can also stimulate yeast, ethanol production, gas and DM losses [5,14]. Additives are used to absorb moisture, inhibit undesirable microorganisms, and improve nutritive value [15]. Castor meal fulfills these roles, acting as a moisture-absorbing, protein-rich additive that improves fermentation, reduces losses, and increases protein content [5,16].

The addition of detoxified castor bean meal increases the DM content, which restricts the proliferation of undesirable microorganisms such as *Clostridia* and gas-producing enterobacteria by reducing water activity [17]. Furthermore, the higher DM content favors the dominance of homofermentative lactic acid bacteria over heterofermentative species, promoting a faster and more efficient pH drop, which is crucial for silage quality [17,18] and improves aerobic stability [16].

Previous studies tested calcium hydroxide-treated castor meal as an additive in sugarcane silage at up to 21% of fresh matter, without negative effects on intake, digestibility, performance, or carcass traits in sheep [10,19,20]. The inclusion of detoxified castor bean meal at levels up to 40% fresh matter in sugarcane silage is supported by experimental evidence from our group [7], which confirmed the absence of toxic effects on sheep blood parameters and organ histology (rumen, liver, and kidneys). This validated safety profile allows for the exploration of inclusion levels significantly higher than the 21% fresh matter limit previously reported in the literature. Given that the proteolytic activity of sugarcane silage may further mitigate toxic risks [4], testing these higher levels is essential to maximize the replacement of soybean meal and improve the economic efficiency of sheep production systems.

Therefore, we hypothesized that sheep could consume silage containing industrially detoxified castor meal without compromising animal performance up to 40% by fresh matter. The aim of this study was to evaluate intake, nutrient digestibility, and productive performance of sheep fed sugarcane silage with increasing levels of detoxified castor meal up to 40% of sugarcane fresh matter.

2. Materials and Methods

All experimental procedures were conducted in accordance with the guidelines established by the Animal Care and Use Ethics Committee of the National Institute of the Semi-Arid Region (INSA/MCTI) (Protocol n° 0001/2021).

2.1. Experimental Site

The experiment was conducted at the Experimental Station of the National Semi-Arid Institute (INSA), located in Campina Grande, State of Paraíba, Brazil, at the following geographic coordinates: latitude 7°13'50" S, longitude 35°52'52" W, and with an average annual rainfall of 492.4 mm and an average temperature of 24.6 °C [21].

2.2. Experimental Animals and Diets

Twenty-four intact ram lambs were considered as experimental units. They had no specific crossbreed, an initial body weight of 16.0 ± 0.75 kg, and were approximately eight months of age. They were housed in individual folds (2.0 m $\times$ 1.1 m) equipped with a drinker and feeder. The animals were identified with earrings, weighed, and dewormed against endo and ectoparasites with Moxidectina at a dose of 1 mL per 50 kg of body weight (BW) (Cydectin, Fort Dodge Animal Health, Campinas, SP, Brazil). Subsequently, they were assigned to a completely randomized design of four treatments, which consisted of four inclusion levels (0, 10, 20, and 40%) of detoxified castor meal (DCM) into sugarcane silage on a fresh matter (FM) basis. Twenty-four intact ram lambs were randomly assigned to a completely randomized design consisting of four treatments with six replications (animals) per treatment. The experimental period lasted 60 days, with 10 days for adaptation (management practices and diets) and 50 days for data and sample collection.

The experimental diets were formulated to be isonitrogenous and isoenergetic to meet the nutritional requirements of sheep for an average daily gain of 0.150 kg/day, according to the recommendations of the NRC [22]. The composition of the experimental diets is listed in Table 1. The sugarcane (*Saccharum officinarum*) used in the experiment was harvested 16 months after regrowth. The forage was chopped in a stationary forage machine into particles with an average size of 10 ± 12 mm. After processing, the sugarcane was homogenized and mixed with the DCM corresponding to the amount of each treatment.

Table 1. Chemical composition of the silage treatments and of the ingredients used for formulation of the experimental diets.

Nutritional Characteristic (g/kg of Dry Matter)	Castor Meal Dose ¹ (% Fresh Matter)				Castor Meal	Ground Corn	Soybean Meal	Sugarcane
	0%	10%	20%	40%				
Dry matter (g/kg fresh matter)	213.63	232.13	269.26	308.67	865.45	856.60	873.61	301.52
Mineral matter	71.90	73.96	97.07	84.21	103.70	20.29	64.98	75.25
Organic matter	928.10	926.04	902.93	915.79	896.30	979.71	935.02	943.47
Crude protein	43.90	97.40	140.10	182.20	380.10	85.60	491.20	46.33
Ether extract	34.55	59.04	44.73	48.07	7.68	66.89	134.57	38.80
Neutral detergent fiber	707.98	599.58	608.92	532.97	412.98	249.46	235.36	715.31
Acid detergent fiber	176.00	160.45	128.50	138.60	64.10	14.30	36.40	194.65
Total carbohydrates	849.65	769.60	718.10	685.53	508.52	827.21	309.24	855.345
Non-fiber carbohydrate	141.68	170.02	149.18	152.55	95.54	577.75	73.88	146.67

¹ Castor meal dose (DCM) (0, 10, 20, and 40% on a natural matter [NM] basis of sugarcane silage) is equivalent to 0, 5, 10, and 20%, respectively, on a natural matter basis of the total diet.

The DCM was supplied by Azevedo Óleos Vegetais LTDA. (Itupeva, SP, Brazil). The detoxification and processing followed a multi-stage industrial protocol. Initially, the seeds underwent mechanical cleaning using high-capacity shaking sieves and air-blowing systems (Bühler TASTM cleaning series, Uzwil, Switzerland) to remove impurities. Oil extraction was performed in two phases: first, mechanical extraction using an expeller press (International Expeller[®], Cleveland, OH, USA), reducing the oil content. This was followed by chemical extraction using hexane as a solvent at 60 °C for 2:30 h in a horizontal belt (De Smet Extraction Technology[®], Diegem, Belgium), further reducing the residual oil. Finally, the solvent was removed through an evaporation process in a desolventizer-toaster or industrial oven at 100 °C for 2 h (Estufa Industrial AC-0025, Ar Brasil, Equipamentos Industriais LTDA, São Paulo, SP, Brazil). After processing, the sugarcane and DCM were ensiled in bag silos (high-density bags, measuring 51 × 110 cm, 50 kg). The material was manually compacted by human trampling to minimize the amount of oxygen inside the silos and ensure adequate anaerobic conditions.

Silos were opened after 60 days of fermentation, and the silages were sampled for laboratory analysis. Corn and soybean meal concentrates were formulated to compose the animal diet (Table 2). The lambs were given a total mixed ration (TMR) twice a day, at 8:00 and 16:00 h. The amount of feed offered and the leftovers were weighed daily to measure voluntary intake, respecting a level of 10% leftovers. Samples of the diet provided and the leftovers were collected daily and frozen at −20 °C for analysis. Subsequently, the samples were thawed, homogenized, weighed, and pre-dried in a forced air oven at 55 °C for 72 h.

Table 2. Proportion of ingredients in the experimental diets and chemical composition of experimental diets.

Ingredients (% Fresh Matter)	Castor Meal Dose ¹ (% Fresh Matter)			
	0%	10%	20%	40%
Detoxified castor meal	0.00	4.75	9.51	19.01
Ground corn	31.46	35.41	40.40	50.38
Soybean meal	18.77	14.97	9.98	0.00
Sugarcane	47.53	42.77	38.01	28.51
Urea	0.14	0.00	0.00	0.00
Mineral mix	1.14	1.14	1.14	1.14
Ammonium chloride	0.95	0.95	0.95	0.95
Ammonium sulfate	0.01	0.01	0.01	0.01
Nutritional characteristic (g/kg of dry matter) ²				
Dry matter (g/kg fresh matter)	557.18	587.30	617.47	677.80
Mineral matter	52.75	52.60	51.88	50.44
Organic matter	924.85	926.50	927.22	928.66
Crude protein	143.94	140.68	136.44	127.90
Ether extract	62.73	58.98	54.32	45.01
Neutral detergent fiber	459.16	446.06	432.72	406.10
Acid detergent fiber	94.98	88.85	82.42	69.58
Total carbohydrates	722.13	726.85	736.45	755.74
Non-fiber carbohydrates	262.97	280.79	303.74	349.64
Total digestible nutrients	797.04	772.05	743.26	685.71

¹ Castor meal dose (DCM) (0, 10, 20, and 40% on a natural matter [NM] basis of sugarcane silage) is equivalent to 0, 5, 10, and 20%, respectively, on a natural matter basis of the total diet. ² Nutritional characterization of the experimental diets expressed in grams per kilogram based on dry matter basis of the total diet.

2.3. Sampling, Animal Performance and Nutrients Used

The animals were weighed every two weeks on an electronic scale after a 16 h fast to facilitate precise measurements of animal performance. Initial body weight (IBW) was obtained by weighing the animals on the first experimental day. The last weighing was performed on the last experimental day to obtain the final body weight (FBW) and evaluate animal performance. Weight gain (WG) was estimated by the equation: $WG = FBW - IBW$; average daily gain (ADG) was calculated by the equation: $ADG = (FBW - IFW) / \text{feedlot period}$. Feed efficiency (FE) was calculated as follows: $FE = \text{kg BW gain} / \text{kg feed}$.

Dry matter intake (DMI) was calculated by the difference between the total DM of the supplied feed and the total DM in the leftovers. Nutrient intake was determined by the difference between the total nutrients in the feed ingested and the total nutrients in the leftovers, based on the total DM.

To determine the apparent digestibility coefficients of DM, organic matter (OM), CP, neutral detergent fiber (NDF), and EE, after the 46th day of the feedlot period, feces were collected directly from the rectal ampoule of the animals. Fecal samples were collected twice a day for three consecutive days at alternating times throughout the collection days (47th day at 6:00 and 14:00 h, 48th day at 8:00 and 16:00 h, and 49th day at 10:00 and 18:00 h), according to Bispo et al. [23]. Subsequently, the feed samples were weighed, pre-dried, and placed into nonwoven fabric bags (100 g/m²), previously dried and weighed, and incubated in the rumen of a fistulated male bovine for 288 h, according to the in situ protocol [24]. After incubation, the bags were treated with a neutral detergent solution for 60 min, washed under running water and subsequently with hot distilled water. They were then immersed in acetone for 5 min, dried at 105 °C for 12 h, and weighed for the determination of indigestible neutral detergent fiber (iNDF). All procedures followed the standardized analytical methods of the National Institute of Science and Technology in Animal Science by Detmann et al. [25]. Fecal DM was estimated based on iNDF levels. Digestibility coefficients (DCs) of nutrients were calculated using the equation proposed by Silva and Leão [26]: $DC = [(\text{kg of ingested fraction} - \text{kg of excreted fraction}) / (\text{kg ingested fraction})]$.

2.4. Laboratory Analysis

At the end of the experiment, the feed and leftover samples were thawed and pooled according to the experimental treatments. For the digestibility analysis, the leftovers, feed, and feces were grouped by animal. These samples were ground using a Wiley mill with a 1-mm sieve for the analyses of DM (method 934.01), ash (method 942.05), CP (Kjeldahl, $N \times 6.25$, method 981.10), and EE (method 920.39), according to AOAC (1997) [27]. The analysis of NDF was performed using thermostable amylase, according to the methodology described by Detmann et al. [25]. Total carbohydrates (TC) were determined according to Sniffen et al. [28] and calculated using the following equation: $TC (\text{g/kg DM}) = 100 - (CP + EE + \text{Ash})$.

Non-fiber carbohydrates (NFC) were calculated according to Hall [29], using the following equation: $NFC = 100 - \text{Ash} - EE - \text{NDF} - (CP + \text{CPu} + U)$, where: CPu = crude protein content from urea, U = urea content.

The total digestible nutrient (TDN) content was estimated using the equation proposed by Weiss et al. [30]: $TDN = \text{CPdigestible} + (\text{EEdigestible} \times 2.25) + \text{NFCdigestible} + \text{NDFdigestible}$.

2.5. Statistical Analysis

The results were subjected to analysis of variance (ANOVA) and regression using the statistical software SISVAR version 5.6 [31]. To evaluate the effect of inclusion levels of detoxified castor bean meal in sugarcane silage, inclusion levels were considered as a quan-

titative independent variable, and response variables were treated as dependent variables. Linear and quadratic regression models were fitted according to the observed biological response. Regression equations were selected based on the coefficient of determination (R^2), considering linear and quadratic effects. The significance of regression coefficients was determined using the T test, adopting a significance level of 5% ($\alpha = 0.05$), according to the model:

$$Y_{ij} = \beta_0 + \beta_1 X_i + \beta_2 X_i^2 + e_{ij}$$

where Y_{ij} = observed variable; β_0 = overall mean; β_1 = coefficient do efeito linear; β_2 = coefficient do efeito quadrático; X_i = effect of the inclusion level of detoxified castor bean meal; e_{ij} = effect associated with the experimental error.

3. Results

The inclusion of increasing levels of detoxified castor meal (DCM) in sugarcane silage likely promoted an improvement in its nutritional value. A progressive increase in crude protein (CP) content was observed as DCM levels increased. Conversely, a dilution effect of the fibrous fraction was observed, as evidenced by reductions in neutral detergent fiber (NDF) and acid detergent fiber (ADF) contents (Table 1).

The inclusion of different doses of castor meal in sugarcane silage did not affect DMI, organic matter intake (OMI), neutral detergent fiber intake (NDFI), total carbohydrate intake (TCI), or non-fiber carbohydrate intake (NFCI), as shown in Table 3. However, an effect was observed on crude protein intake (CPI) and ether extract intake (EEI), both showing a decreasing linear trend ($p \leq 0.05$), indicating that increasing DCM levels in silage reduced the intake of these nutrients. Specifically, CPI decreased from 0.157 kg/day in the control group (0% DCM) to 0.128 kg/day at the 40% inclusion level. Likewise, EEI dropped from 0.068 to 0.044 kg/day over the same range of DCM inclusion.

Table 3. Nutrient intake of sheep feeding on sugarcane silage containing increasing doses of detoxified castor meal and significance of the linear regression.

Nutrient Intake (kg/day)	Castor Meal Dose ¹ (% Fresh Matter)				SEM ²	p-Value ³	
	0%	10%	20%	40%		L	Q
Dry matter based on body weight (kg)	4.579	4.630	4.411	4.533	0.16	0.706	0.657
Dry matter (g/kg ^{0.75}) ⁴	1.065	1.094	0.999	1.068	0.03	0.778	0.360
Dry matter	1.049	1.120	1.001	1.095	0.68	0.516	0.953
Organic matter	0.969	1.038	0.927	0.946	0.63	0.550	0.948
Crude protein ⁵	0.157	0.151	0.135	0.128	0.09	0.038	0.906
Ether extract ⁶	0.068	0.065	0.055	0.044	0.03	0.001	0.827
Neutral detergent fiber	0.464	0.487	0.416	0.412	0.29	0.108	0.926
Total carbohydrate	0.754	0.814	0.735	0.773	0.50	0.971	0.989
Non-fiber carbohydrate	0.515	0.552	0.506	0.559	0.24	0.357	0.642

¹ Castor meal dose (DCM) (0, 10, 20, and 40% on a natural matter [NM] basis of sugarcane silage) is equivalent to 0, 5, 10, and 20%, respectively, on a natural matter basis of the total diet. ² SEM: standard error of the mean.

³ p-value: significant p-value ($p < 0.05$) for linear (L) or quadratic (Q) order effects. ⁴ 0.75: Metabolic weight;

⁵ Crude protein: $Y = 0.1553 - 0.0006x$ ($R^2 = 0.7504$); ⁶ Ether extract: $Y = 0.0696 - 0.0006x$ ($R^2 = 0.9739$).

Regarding nutrient digestibility (Table 4), the doses of DCM did not affect the digestibility of dry matter (DMD), organic matter (OMD), neutral detergent fiber (NDFD), total carbohydrates (TCD), or non-fiber carbohydrates (NFCD). However, an impact was observed on the digestibility of crude protein (CPD) and ether extract digestibility (EED). CPD dropped sharply from 754.15 g/kg at 0% DCM to 472.88 g/kg at 40% DCM, while EED declined from 813.02 to 725.08 g/kg.

Table 4. Nutrient digestibility of sheep feeding on sugarcane silage containing increasing doses of detoxified castor bean meal and the significance of the linear regression.

Digestibility of Nutrients (g/kg)	Castor Meal Dose ¹ (% Fresh Matter)				SEM ²	p-Value ³	
	0%	10%	20%	40%		L	Q
Dry matter	909.58	899.06	920.54	890.60	8.39	0.207	0.189
Organic matter	713.11	689.93	721.79	654.20	22.09	0.096	0.332
Crude protein ⁴	754.15	669.74	665.19	472.88	36.40	0.001	0.436
Ether extract ⁵	813.02	802.42	783.73	725.08	23.83	0.018	0.429
Neutral detergent fiber	582.19	536.92	606.20	514.28	32.23	0.247	0.389
Non-fiber carbohydrate	882.17	907.64	882.19	869.66	17.43	0.368	0.454
Total carbohydrate	697.49	686.25	726.08	680.32	22.57	0.733	0.345

¹ Castor meal dose (DCM) (0, 10, 20, and 40% on a natural matter [NM] basis of sugarcane silage) is equivalent to 0, 5, 10, and 20%, respectively, on a natural matter basis of the total diet. ² SEM: standard error of the mean. ³ p-value: significant p-value ($p < 0.05$) for linear (L) or quadratic (Q) order effects. ⁴ Crude protein: $Y = 758.8466 - 6.7633x$ ($R^2 = 0.9423$); ⁵ Ether extract: $Y = 816.7708 - 2.0404x$ ($R^2 = 0.7888$).

Concerning sheep performance, none of the performance variables measured were affected by the different doses of DCM in the silage (Table 5). Total weight gain during the experimental period ranged from 6.19 to 7.05 kg, with no statistical association with the castor meal levels. Similarly, variations in average daily gain and feed efficiency were not affected by the tested inclusion levels ($p \geq 0.05$).

Table 5. Performance of sheep feeding on sugarcane silage containing increasing doses of detoxified castor meal and the significance of the linear regression analysis.

Performance Indicator (kg)	Castor Meal Dose ¹ (% Fresh Matter)				SEM ²	p-Value ³	
	0%	10%	20%	40%		L	Q
Final body weight	23.85	24.39	22.75	24.15	9.27	0.995	0.490
Weight gain	6.19	6.99	6.32	7.05	5.60	0.415	0.992
Average daily gain (kg/day)	0.15	0.14	0.13	0.14	0.11	0.428	0.985
Feed efficiency	0.111	0.118	0.126	0.130	0.08	0.103	0.585

¹ Castor meal dose (DCM) (0, 10, 20, and 40% on a natural matter [NM] basis of sugarcane silage) is equivalent to 0, 5, 10, and 20%, respectively, on a natural matter basis of the total diet. ² SEM: standard error of the mean. ³ p-value: significant p-value ($p < 0.05$) for linear (L) or quadratic (Q) order effects.

4. Discussion

The main finding of this study was that industrially, DCM can be safely used as an additive in sugarcane silage, replacing soybean meal up to 40% fresh matter DCM in sugarcane silage, without impairing feed intake, digestibility, or animal performance. The absence of negative effects on growth performance and intake indicates that the detoxification process adopted by the oil extraction industry and fermentation process, ensilage was effective in eliminating ricin toxicity to levels safe for ruminant feeding.

DMI and the intake of other nutrients, such as organic matter and NDF, were not affected by the DCM doses. These findings suggest that the inclusion of DCM in sugarcane silage did not alter feed palatability or ruminal fermentation patterns enough to affect voluntary intake. Our findings are consistent with previous studies evaluating the inclusion of DCM in the diets of small ruminants. Oliveira et al. [5], when evaluating inclusion levels of 0, 7, 14, and 21 of DCM on a fresh matter basis in sugarcane silage, and Paulino et al. [16], testing levels of 0, 5, 10, 15, and 20% of DCM under the same conditions, recommend the highest DCM inclusion levels (21 and 20%, respectively), due to improvements in CP content and improvements in the fermentation profile of the silage. In this context, Lira et al. [20], when evaluating the use of sugarcane silage containing DCM (0, 5, 10, 15, and

20% on a fresh matter basis in sugarcane silage) in diets for sheep, also recommended the highest evaluated level (20% DCM in the silage). The maintenance of soybean meal in the diet (54 g/kg) contributed to increased nutrient intake and feed efficiency. However, these authors observed a reduction in OMD and CPD.

Lima et al. [9], when evaluating goat diets using sugarcane silage containing increasing levels of DCM (0, 2.5; 5; and 7.5% on a fresh matter in basis sugarcane silage) added with urea, observed that the 2.5% level ensures improvements in milk composition and production and feed efficiency of goats, without negatively affecting nutrient intake, digestibility, or ingestive behavior. According to Dantas Júnior et al. [32], moderate inclusion levels of DCM (up to 20% on a DM or as-fed basis) can even promote beneficial ruminal and intestinal morphological changes that enhance nutrient absorption in small ruminants. It is essential to emphasize that, although our inclusion levels in the sugarcane silage were 0, 10, 20, and 40% DCM (on an as-fed silage basis), these are equivalent to 0, 5, 10, and 20% DCM on an as-fed diet basis, as detailed in Table 2. Therefore, our results corroborate the aforementioned studies while expanding the safe limit for inclusion in silage, demonstrating the feasibility of utilizing DCM as an additive at higher levels without compromising animal performance.

The decrease in CPI and CPD observed in this study reflects the lower biological value of the protein in DCM compared to soybean meal. This reduction can be explained by the heat and alkaline conditions involved in castor oil extraction, which may promote protein denaturation and reduce nitrogen availability [3,18,19,33,34].

Additionally, Corrêa et al. [7], in a complementary histological study using sheep fed sugarcane silage supplemented with DCM at the same inclusion levels of our study (0, 10, 20, and 40% DCM fresh matter in sugarcane silage) are equivalent to 0, 5, 10, and 20% DCM on an as-fed diet basis, reported morphological changes in the ruminal epithelium, including increased papilla width and keratinization at the highest inclusion level (up to 40%). These adaptations indicate a physiological adjustment of the ruminal mucosa to the presence of DCM, which may slightly reduce nutrient absorption efficiency, particularly for CP. The increased keratinized layer, while not pathological, may act as a physical barrier, contributing to the lower CPD values observed in this experiment. The results indicate that replacing soybean meal with detoxified castor meal, when performed without urea supplementation, compromises the biological value of nutrients, particularly protein, resulting in reduced dietary protein digestibility. In the study by Ferreira et al. [10], even at the highest inclusion level evaluated (20%), the maintenance of soybean meal in the diet (54 g/kg) contributed to higher intake and improved crude protein digestibility. In contrast, Lima et al. [9] observed that the complete replacement of soybean meal at the highest inclusion level (75 g/kg dry matter of detoxified castor meal), when associated with urea supplementation (14 g/kg), did not result in losses in the biological value of nutrients, particularly protein. These findings highlight the importance of adequate protein balance and sufficient ruminal nitrogen availability to sustain fermentation efficiency and the utilization of alternative protein sources to soybean meal in ruminant nutrition.

Ether extract intake and EED also showed a decreasing trend as DCM replaced soybean meal. This pattern is mainly due to the markedly lower lipid content of DCM (7.68 g/kg) compared to soybean meal (134.57 g/kg). However, the unique lipid profile of castor oil, dominated by ricinoleic acid, a hydroxylated fatty acid, could also influence ruminal lipid metabolism. Despite being metabolizable by rumen microbiota, ricinoleic acid has an unusual chemical structure that may limit its hydrogenation and absorption [35,36]. The histological observations from Corrêa et al. [7] further support this interpretation, as the ruminal epithelial thickening and keratinization associated with higher DCM inclusion

(up to 40% DCM fresh matter in sugarcane silage) could impair lipid absorption efficiency, aligning with the reduced EED observed in our study.

Regarding animal performance, no effects were detected for total weight gain, average daily gain (ADG), or feed efficiency (FE). The stable performance, despite the reduction in CP and EE digestibility, indicates that the energy and protein supply from the silage remained adequate to meet the maintenance and growth requirements of the animals. These results align with previous findings [16,32], showing that the inclusion of DCM up to moderate levels (up to 40% DCM fresh matter in sugarcane silage) in the diet of small ruminants does not compromise productive performance.

The complementary histological findings of Corrêa et al. [7] help explain the maintenance of performance even at higher DCM inclusion levels (up to 40% DCM fresh matter in sugarcane silage). The authors reported that DCM inclusion increased ruminal papilla width, stimulating microbial activity and volatile fatty acid (VFA) production, especially propionate and butyrate, which are key precursors for gluconeogenesis and energy metabolism in ruminants. Therefore, even with reduced protein digestibility, the increased fermentation surface and VFA production could have compensated for potential reductions in nutrient availability, maintaining satisfactory performance.

Overall, the results of this study demonstrate that the inclusion of industrially detoxified castor meal (up to 40% DCM fresh matter in sugarcane silage) provides a safe and efficient feeding strategy for sheep. The observed adjustments in nutrient intake and digestibility are compatible with normal physiological adaptations of the digestive system, without indicating any toxic or pathological effects. The balance between feed composition, ruminal adaptation, and microbial fermentation contributed to maintaining stable performance parameters, even at the highest inclusion levels (up to 40% DCM fresh matter in sugarcane silage). These findings support the use of detoxified castor meal as a sustainable alternative protein source in ruminant diets, offering nutritional and environmental benefits for livestock production systems in semi-arid regions.

5. Conclusions

Sheep feeding on sugarcane silage made with detoxified castor meal at a large scale in the castor oil industry had good performance, such as in the diet with soybean meal as the protein source. Increasing doses of detoxified castor meal in the sugarcane silage, up to 40% by fresh matter, did not influence sheep performance.

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Abbreviations

The following abbreviations are used in this manuscript:

CP	Crude protein
EE	Ether extract
DM	Dry matter
BW	Body weight
INSA	Experimental Station of the National Semi-Arid Institute
DCM	Detoxified castor meal
TMR	Total mixed ration
IBW	Initial body weight
FBW	Final body weight
WG	Weight gain
ADG	Average daily gain
FE	Feed efficiency
DMI	Dry matter intake
OM	Organic matter
NDF	Neutral detergent fiber
iNDF	Indigestible neutral detergent fiber
DC	Digestibility coefficients
TC	Total carbohydrates
CPu	Crude protein content from urea
NFC	Non-fiber carbohydrates
TDN	Total digestible nutrient
OMI	Organic matter intake
NDFI	Neutral detergent fiber intake
TCI	Total carbohydrate intake
NFCI	Non-fiber carbohydrate intake
CPI	Crude protein intake
EEI	Ether extract intake
DMD	Dry matter digestibility
OMD	Organic matter digestibility
NDFD	Neutral detergent fiber digestibility
TCD	Total carbohydrate digestibility
NFCD	Non-fiber carbohydrates digestibility
CPD	Crude protein digestibility
EED	Ether extract digestibility
VFA	Volatile fatty acid

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