

Article

The Effect of Clayey Micromineral Compounds in Lamb Feed on Health, Intake, Performance, and Carcass and Meat Quality Parameters

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Simple Summary

Raising healthy and productive animals is a major goal for farmers, but feed supplements must be safe, affordable, and effective. In this study, we tested whether adding a natural clay-based micromineral compound (CMC) to the diet of feedlot lambs could improve their health, feed use, and meat quality. Twenty-four lambs were fed diets containing 0%, 0.4%, 0.8%, or 1.2% CMCs for 90 days. The results showed that a moderate CMC dose (0.8%) improved digestion and nutrient use, while higher doses affected meat color, making it darker and more appealing to consumers. Blood tests suggested that the supplement supported liver health without causing harm. Although overall growth and carcass yield did not change significantly, these findings indicate that CMCs can be used safely at moderate levels to improve feed efficiency and meat appearance. This offers a simple, low-cost strategy that may help farmers raise healthier animals and produce more attractive meat for consumers.

Abstract

Improving livestock nutrition with natural supplements can enhance productivity and meat quality. This study evaluated whether a clayey micromineral compound (CMC) in lamb diets improves feed efficiency, health, and meat traits. Twenty-four 60-day-old Dorper/Santa Inês crossbred lambs (28.41 ± 4.147 kg initial weight) were randomly assigned to four CMC doses (0%, 0.4%, 0.8%, or 1.2% of dry matter intake/day) for 90 days, following a 15-day adaptation. The lambs were individually housed, with daily feed intake monitoring, weekly weight measurements, and blood analyses at the start and end. On day 89, rumen fluid was sampled for digestion analysis, and post-mortem evaluations were used to assess meat quality and rumen health. The results showed that 0.8% CMC optimized fat and fiber digestion ($p < 0.05$), while higher doses linearly improved meat color intensity ($p < 0.05$). Blood tests indicated better liver function at intermediate doses ($p < 0.05$). However, the CMC did not affect overall growth, feed intake, or carcass traits. The supplement was



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safe but provided selective benefits. These findings suggest that CMCs could enhance feed efficiency and meat appeal, although further research is needed to refine dosing for maximum impact.

Keywords: adsorbent; clay minerals; enterosorption; feedlot; feed additive; lamb nutrition; lamb performance; meat quality

1. Introduction

Feed accounts for up to 70% of sheep production costs, making strategies that enhance feed efficiency essential [1]. Proper functioning of the gastrointestinal tract (GIT) is crucial in this context. Clay mineral compounds (CMCs) have emerged as feed additives capable of improving gut health, enhancing immunity, and ultimately promoting animal performance [2,3]. Beyond these benefits, their technological and functional properties in animal nutrition deserve further consideration.

Clayey mineral compounds, such as bentonite, montmorillonite, smectite, and others, are already marketed as anti-caking additives in feed for production animals [4]. In addition to this function, studies indicate that CMCs have additional properties, such as the ability to adsorb mycotoxins and other contaminants in the GIT through enterosorption, thereby reducing the negative impact of these substances on animal health [5]. This improves the integrity of the GIT, increasing the animal's immunity and, consequently, production efficiency.

Mycotoxins produced by fungi, such as *Aspergillus* and *Fusarium*, cause disorders and diseases in farm animals [6] and can be present in feed even before they are ingested by sheep in varying proportions [7]. Fungi develop in both roughage sources (pasture or stored forage) and grains (e.g., corn and soybean) used in concentrate formulation [8]. Once in the GIT of these animals, the intoxication can occur, impairing the mobilization of nutrients to a greater or lesser extent.

In this sense, the use of CMCs becomes more interesting for small ruminants, since they are more sensitive and susceptible to poisoning due to their habit of selectively grazing younger leaves close to the soil, where the concentration of mycotoxin can be higher [9]. This reinforces the importance of nutritional strategies to ensure the health and performance of these animals. In addition, these additives have a low application cost and can be easily incorporated into the diet in low concentrations, without compromising the performance of the animals [10].

However, studies have shown that CMCs nutritionally improve the efficiency of nutrient absorption in the GIT [11]. This is due to the improvement in GIT immunity, which increases its capacity for nutrient absorption; in addition, it promotes reduced nutrient degradation in the rumen, increasing the rate of passage of important nutrients, such as rumen undegradable protein (RUP), for example [12], improves short-chain fatty acid (SCFA) production, and reduces methane gas emission [13]. As a consequence, it improves the productive performance of animals. Nevertheless, the literature presents divergent findings regarding the magnitude of these effects, which may vary depending on ruminant species, diet composition, and inclusion level [2,5].

Research on the effects of clay mineral compounds (CMCs) on carcass and meat traits in ruminants remains limited. Therefore, this study aimed to evaluate the inclusion of different CMC doses (0.00%, 0.40%, 0.80%, and 1.20% DM/animal/day) in the diets of growing and finishing lambs. We assessed their impact on blood and rumen health parameters, feed intake, performance, and carcass and meat quality. We hypothesized

that dietary CMC supplementation would improve gastrointestinal health and immunity, enhancing nutrient utilization, productive performance, and carcass and meat quality in lambs.

2. Materials and Methods

The experimental activities were conducted on the premises of the Goat and Sheep Production Sector of the Department of Animal Science (DZO) of the Federal University of Goiás (UFG) (coordinates: latitude 16°35'55.158" S, longitude 49°16'36.498" W; altitude 739.39 m), between 2 September and 1 December 2023.

2.1. Animal Ethics Statement

All experimental activities were submitted for evaluation and approved by the Ethics Committee on the Use of Animals (CEUA) of UFG, under protocol number 030/23. Sample collection, in addition to handling the animals, was carried out by properly trained and qualified people.

Justification of the Number of Animals

To adjust the number of animals (n) to meet the conditions of the facility at the Center for the Study of Goats and Sheep of the School of Veterinary and Animal Science of UFG and the minimum use of animals, the final weight (FW) variable was considered, using as a basis the animal data of the last experiments conducted at the Sheep Management Center of the Água Limpa Farm of the University of Brasília (CMO/FAL/UnB). The equation (Equation (1)) below was used:

$$n = \left(\frac{Z_{(1-\alpha)} * DP}{d} \right)^2 \quad (1)$$

where n = sample size; $Z_{(1-\alpha)}$ = value Z of the standard normal curve for the degree of confidence ($1 - \alpha$), e.g., $Z = 1.96$ if $1 - \alpha = 95\%$ or $Z = 2.58$ if $1 - \alpha = 99\%$; SD = population standard deviation of the variable; and d = desired accuracy, usually $\pm 5\%$ of the expected mean ($1.05 \times \text{mean}$)

A standard normal curve was considered for the 95% confidence level. To calculate the standard deviation, we used FW data as a basis. The lightest animal in this experiment weighed 29.25 kg, and the heaviest weighed 48.25 kg, with a difference of 18.80 between the lowest and highest weight. Thus, the DP estimates that 1/4 of this difference is equal to 4.7 kg. And finally, an accuracy of 5%, in the expected average weight of 38.0 kg, is equivalent to 1.90 kg, more or less. Applying these data to the variable of the final weight of the animals in the equation (Equation (1)), the number of animals needed (n) would be:

$$n = \left(\frac{1.96 * 4.7}{1.90} \right)^2 \quad (2)$$

$$n = 23.5071 \quad (3)$$

That is, after rounding to 24 animals, 6 animals were used per treatment.

Clear inclusion and exclusion criteria were applied to ensure homogeneity among the experimental units. All lambs used in this study were males of similar genetic background, with comparable initial body weight and age. The animals were clinically healthy and showed no signs of disease or physical abnormality before the trial. Experimental units were standardized according to the mean body weight of the groups, ensuring similar conditions among treatments. Each experimental group consisted of six lambs ($n = 6$), corresponding to the four CMC inclusion levels evaluated.

2.2. Animal Feed Distribution and Management

A total of 24 crossbred Dorper/Santa Inês lambs were used, weaned at 60 days, with an average weight of 28.41 kg ($\pm$ 4.147). They were distributed in weight-standardized lots, in a completely randomized design (CRD), in four treatments, with six animals per group and in individual pens. The treatments were as follows: T1 = control (no CMC); T2 = 0.5 g of CMC/3.5 kg of body weight (0.40% of the dry matter (DM) of the daily diet); T3 = 1 g of CMC/3.5 kg of body weight (0.80% DM); and T4 = 1.5 g of CMC/3.5 kg of body weight (1.20% DM).

The experimental period lasted 90 days, with the first 15 days for adaptation to the diet and 75 days for experimental data collection. The diet provided was based on hydrolyzed chopped sugarcane as a source of forage and concentrate in the ratio of 65% forage and 35% concentrate fed twice a day (8 am and 4 pm). The sugarcane was hydrolyzed every two days with livestock urea (1 kg of urea for every 100 kg of chopped sugarcane).

The diet formulations were carried out according to the metabolic requirements recommended by the NRC [14]. All experimental base diets had the same nutritional composition, according to the requirement for each phase, with only the daily dose of CMC (Table 1) adjusted weekly, according to the animals' weight gain.

Table 1. Composition of the ingredients of the experimental diets of feedlot lambs based on dry matter.

Components	Composition (g/kg)		
	Forage Cane	Focused	Total Diet
Dry matter	336.55	893.48	615.00
Crude protein	48.89	191.74	240.63
Ether extract	13.00	38.00	51.00
Mineral matter	34.87	33.86	68.73
Neutral detergent fiber	345.99	207.37	553.36
Acid detergent fiber	164.96	15.54	180.49
Total carbohydrates	903.24	736.40	1639.63
Non-fibrous carbohydrate	557.25	529.03	1086.28
Phosphorus	23.30	22.20	45.50
Calcium	0.80	8.80	9.60
Calcium/phosphorus ratio	0.03	0.40	0.21

Note: Dry matter diet ingredient (g/kg): hydrolyzed sugarcane = 336.55; ground corn = 165.00; soybean meal = 120.00; mineral salt = 25.00 (composition: phosphorus (60 g/kg), calcium (min, 180 g/kg), chlorine (100 g/kg), sodium (114 g/kg), fluoride (max, 500 n.s./kg), cobalt (50 mg/kg), magnesium (10 g/kg), sulfur (8 g/kg), manganese (1 g/kg), iodine (60 mg/kg), zinc (240 mg/kg), copper (130 mg/kg), selenium (12 mg/kg); and urea = 10.00.

The dose of CMC was offered daily to the lambs in the different treatments only in the morning, mixed in 1/6 of the portion of the concentrate in the morning, in individual feed troughs, after weighing the morning trough leftovers and before offering the diet, weighed daily in the morning and afternoon. After the lambs consumed the total mixture of CMC with the concentrate, sugarcane was offered with the rest of the morning concentrate. The same procedure was repeated for the animals in the control treatment.

The diet adjustment calculation was performed considering the weight of the animals (measured weekly, on Mondays) and the leftovers in the troughs. The amount of concentrate offered daily was based on the total intake of 4% of the live weight of the animals. The animals had free access to clean and potable water.

2.3. Composition of Clay Trace Mineral Compound

The clayey mineral compound (CMC/anti-caking additive) that was used consisted of SiO₂ (51.84%), TiO₂ (1.72%), Al₂O₃ (12.53%), Fe₂O₃ (13.88%), MnO (0.21%), MgO (6.21%),

CaO (9.70%), Na₂O (2.20%), K₂O (0.96%), P₂O₅ (0.19%) and SO₃ (traces). In addition, it also contained elements of lower concentrations (ppm), such as Sc (scandium, 41 mg/kg), Zn (zinc, 86 mg/kg), Cu (copper, 211 mg/kg), Co (cobalt, 28 mg/kg), Rb (rubidium, 23 mg/kg), Ni (nickel, 68 mg/kg), Cr (chromium, 76 mg/kg), V (vanadium, 301 mg/kg), Sr (strontium, 243 mg/kg), Y (yttrium, 26 mg/kg), Nb (niobium, 10 mg/kg), and Ba (barium, 260 mg/kg).

The chemical and mineralogical characterization report of the CMC used in this research was conducted at the Regional Center for Technological Development and Innovation of the Federal University of Goiás (CRTI-UFG), registered under proposal number 1758/2021.

This compound is already marketed as an anti-caking additive and is registered with the Ministry of Agriculture, Livestock, and Supply. Its composition is similar to bentonite clay, which is used as a technological additive in animal feed, as well as in different applications, as investigated in Gouda et al. [12] and Jiang et al. [15].

2.4. Hemogram and Biochemical Analysis of Blood Parameters

Blood samples were collected from the lambs in the morning before feeding at the beginning of the experiment and two days before slaughter. Each blood sample was obtained by jugular venipuncture, using a vacuum tube (Vacutainer[®], Vacuplast, Cotia-SP, Brazil) and specific needles for collection (0.8 × 25 mm). Two different tubes were used per animal, identified by animal number and treatment: one for biochemical analysis (yellow cap), with coagulant additive gel, and the other for hemogram analysis (purple cap), with EDTA anticoagulant (ethylenediaminetetraacetic acid). After collection, the tubes were gently inverted for one minute to ensure complete mixing of the additives with the blood. Then, they were placed in a thermal box with ice for transport to the Veterinary Clinical Pathology Laboratory, where the samples were immediately analyzed.

The biochemical analyses were performed using diagnostic kits with enzymatic methodological principles from the companies Labtest Diagnóstica[®] S.A. (Lagoa Santa MG, Brazil), BioClin[®] (Belo Horizonte-MG, Brazil) and Randox[®] (São Paulo-SP, Brazil), following their respective protocols. The reading was performed on an automated equipment COBAS MIRA PLUS (Roche[®], Anápolis-GO, Brazil), specific for biochemical analysis. The serum metabolites evaluated as health indicators were total protein (TP), albumin (ALB), alkaline phosphatase (FA), triglyceride (TRI), aspartate-aminotransferase (AST), alanine aminotransferase (ALT), gamma-glutamylpeptidase (GGT), urea (BUN), and creatine (CREAT), which was measured by spectrophotometry using specific commercial kits (LABTEST, Lagoa Santa-MG, Brazil).

The following indicators of erythrogram components were evaluated in the hematological analyses: red blood cells, hematocrit, hemoglobin, mean corpuscular volume (MCV), mean corpuscular hemoglobin concentration (MCHC), total plasma protein, and fibrinogen. The indicators of the leukogram included leukocytes, neutrophils, metamyelocytes, band cells, segmented cells, lymphocytes, monocytes, eosinophils, and basophils.

2.5. Evaluation of Rumen Lesions and Score Histology

The evaluation of the rumen lesion score and the collection of 1 cm² rumen samples for histological analysis were performed after the animals were slaughtered. The slaughter was carried out in a commercial slaughterhouse accredited for sheep. The animals were stunned by electroshock using electrodes positioned behind the ears, with an amperage of 1 A 350 V and subsequent bleeding through the cutting of the jugular vein and carotid artery [16]. Pre-slaughter management was carried out with 12 h of fasting and respect for animal welfare hygienic-sanitary standards.

To evaluate the ruminal lesion score (RLS), a scoring pattern ranging from 0 to 10 points was adopted, with each point corresponding to a 10% increase in lesion involvement, as described by Bigham and McManus [17], where 0 points means no injury and 10 points equals a critical state of injury, without rumen villus and the presence of edema (100%). For this purpose, the weighted average of the lesion percentage observed per treatment was calculated. The evaluation was performed after opening and cleaning the rumen with running water. The evaluation was based on the average observation of the rumen opened by three evaluators, on a lighted bench.

A 1 cm² fragment was collected for histological evaluation in the cranial region of the ventral sac of the rumen. The collected fragment was stapled at the end to an equal-sized piece of Styrofoam sheet and immersed in a 10% formalin prefixing solution for six hours in a flask identified by the animal's number. Then, all tissue fragments collected were preserved in 70% alcohol until the slides were assembled, which was carried out within ten days after harvest. The assembly procedures for the histological slides consisted of immersing the tissue fragments in paraffin cubes and 5 mm thick sections of the cubes in a microtome, followed by staining with the hematoxylin–eosin technique [18].

After assembling the histological slides, the width of the base of the papilla (WBP), the width of the top of the papilla (WTP), the height of the papilla (HLP), the thickness of the lamina propria–submucosa (TLPS), and the thickness of the muscular tunic (TMT) of the rumen fragment were measured. The reading was performed using an electron microscope connected to a computer, where the images were analyzed using the Image J program (Version 1.53) [19].

2.6. Analysis of the Profile of Short-Chain Fatty Acids and N-Ammonia in the Rumen Fluid

Rumen fluid samples were collected to analyze the profile of short-chain fatty acids (SCFAs) and ammonia nitrogen concentration (NH₃-N). The collection was performed using a silicone esophageal tube connected to a peristaltic pump (Komoer, Shanghai, China). The equivalent of 250 mL was collected, which was divided into two collection flasks (one for the SCFA profile and the other for NH concentration₃-N), each equivalent to ±125 mL of rumen fluid. In the bottle used to analyze the SCFA profile, the equivalent of 25% metaphosphoric acid (31.75 mL/125 mL of rumen fluid) was added; an additive was not used to analyze the NH₃-N concentration. Both vials were frozen (−20 °C) until analysis. The SCFA profile was analyzed using a gas chromatography GC-2014 (Shimadzu, Barueri-SP, Brazil) device, according to the methodology described by Bhandari et al. [20] and updates from Detmann et al. [18]. The NH₃-N concentration was analyzed using a UV/Visible spectrophotometer device (Espec-UV-5100, Tecnal, Piracicaba-SP, Brazil), according to the methodology described by Detmann et al. [21].

2.7. Analysis of Diet Composition and Trough Surplus

The samples of the diet provided and the trough leftovers were pre-dried in an oven at 55 °C with forced-air ventilation and ground in a Willey mill with a diameter mm sieve to determine the contents of dry matter (MS, Method 925.45b), crude protein (CP, Method 984.13A), and ether extract (EE, Method 960.39). A 1mm sieve was used to determine neutral detergent fiber (NDF, Method 2002.04), acid detergent fiber (FDA, Method 973.18), and ash (MM, Method 923.03) according to AOAC [22]. The percentage of total carbohydrates (TC = 100 − (CP + MM + EE)) and non-fiber carbohydrates (CNF = 100 − (CP + MM + EE + NDF)) was calculated as described by Sniffen et al. [23].

2.8. The Average Daily Consumption of the Diet

The nutrient ADD of the lambs was obtained using Equation (4).

$$NI = [(DMo \times NDMo) - (DMI \times NDML)] / 100 \quad (4)$$

where *NI*: nutrient intake (g); *DMo*: dry matter offered (g); *DMI*: dry matter of leftovers (g); *NDMo*: percentage of the nutrient in the dry matter offered (%); and *NDML*: percentage of the nutrient in the dry matter of the leftovers (%).

2.9. Animal Performance Analysis

The average daily intake (ADI) of the diet was calculated daily by weighing the diet offered and the trough surplus of each lamb in an individual stall. The ADI was calculated as the difference between the diet offered and the leftover trough.

The acceptability of the concentrate with the addition of the CMC was measured by observing the average time in minutes that the animals took to start the intake of the concentrate in the morning before the sugarcane offer for two consecutive days from the beginning of the supply. The evaluations were carried out at 0, 20, and 40 days from the beginning of the experiment with lambs in individual stalls.

In the performance evaluation of the lambs, the average daily weight gain (ADG, g/animal/day) and total weight gain in the period (TWG, kg/animal) were analyzed. ADG was calculated as the difference in lamb weight at each weighing (in kg) divided by the number of days of the interval between one weighing and another. TWG was obtained as the final weight (FW, kg) minus initial weight (IW, kg) (TWG = FW – IW).

The body development of the lambs was evaluated using the morphometric measurements described by Costa Júnior [24] and Costa and Gonzalez [25], which were obtained with measuring tapes and a wooden compass, with the animals standing on the plane and correctly upright on all four legs. Measurements were taken for anterior height, posterior height, body length, thoracic perimeter, rump width, and chest width. The height of the anterior region was measured from the highest point of the interscapular region to the floor. The height of the back was measured from the highest point of the rump to the ground. Body length was measured from the withers to the caudal part of the ischial tuberosity. Chest circumference was measured at the outer circumference of the chest cavity, near the armpits. The width of the rump was measured using a wooden compass positioned with the tips on both sides of the rump and measuring the distance between these two ends with a tape measure. The width of the chest was measured with the tip of the compass on the side of the shoulders, and then the distance between the points was measured.

2.10. Carcass Yield and Quality Analysis

The lambs were slaughtered in a slaughterhouse accredited for sheep. Pre-slaughter management was adopted with 12 h of fasting and respect for animal welfare hygienic-sanitary standards. The live weight at slaughter (LWS), hot carcass weight (HCW), cold carcass weight (CCW), hot carcass yield (HCY), and cold carcass yield (CCY) were recorded, according to the methodology described by Cezar e Souza [26], with adaptations by Hatamleh and Obeidat [27]. Thus, after slaughter, bleeding, and evisceration, the HCW was determined to evaluate the HCY ((HCW/LWS) × 100). Then, the carcasses were refrigerated in a cold chamber at 4 °C for 24 h and, subsequently, they were weighed for the evaluation of the CCY ((CCW/LWS) × 100) [28,29].

The right half carcass of each animal was used to evaluate the leg circumference and the weights of the five main commercial cuts, namely, the neck, shoulder, rib, loin, and shank, according to the methodology described by Xenofonte et al. [30] and adapted by Fabino Neto et al. [31], to calculate the income from the respective cuts. The longissimus

muscle area (LMA), subcutaneous fat thickness (SSE), carcass conformation, carcass finish, and pH and temperature (measured with a Testo 205 portable device) of the hot carcass were determined before refrigeration and after 24 h of refrigeration at 4 °C, in the longissimus dorsi (sirloin), at the height of the 12th and 13th ribs [27]. Meat quality in the dorsi longissimus muscle was analyzed in terms of shear force (meat tenderness), cooking loss, and color parameters (coordinates L^* , a^* , and b^*) using a Minolta CR-400 (Konica Minolta, Nova Lima-MG, Brazil) device. The intensity of the color (C^* , Equation (5)) and the shade of the flesh (H^* , Equation (6)) were calculated using the a^* and b^* coordinates, respectively [32,33].

$$C^* = \sqrt{a^2 + b^2} \quad (5)$$

$$H^* = \text{atan2}(b^* / a^*) \quad (6)$$

2.11. Statistical Analyses

The data initially underwent a normality test (Shapiro–Wilk) and a homoscedasticity test of the variables (Bartlett). Then, an analysis of variance (ANOVA) and a simple polynomial regression of the first and second degree at the 5% significance level ($p < 0.05$) were performed, considering the doses of CMC (control and 0.40%, 0.80%, and 1.20%) as independent sources of variation. The dependent variables were performance, diet intake, yield, and quality of the carcass and meat. When ANOVA detected significant effects ($p < 0.05$), means were compared using Tukey’s test at the 5% significance level. The significant dependent variables ($p < 0.05$) were subjected to a principal component analysis (PCA) to examine the patterns of treatment segregation within the multivariate space. All statistical procedures were performed using the “easyreg” [34] and “easyanova” [35] packages in the R-Studio 4.3.1 program.

3. Results

3.1. Rumen Trait Results

3.1.1. Lesion Score and Rumen Epithelium Histologies

The rumen lesion condition scores of the lambs did not show significant differences ($p > 0.05$) between the different treatments. There were no significant differences ($p > 0.05$) in the microscopic reading of the WBP, WTP, HLP, TLPS, and TMT measurements of the rumen epithelium (Table 2).

Table 2. Evaluation of the rumen lesion score (RMS) and histological measurements of the papillae and ruminal wall mucosa of lambs confined in the growing and finishing phase receiving different doses of the clayey trace mineral compound (CMA) in the diet.

Variables	Treatments (% in DM) ¹				EPM ²	p-Value	
	0.00	0.40	0.80	1.20		L^3	Q^4
Rumen lesion score ⁵ , %	5	25	5	20	0.293	0.393	0.601
Width of the base of the papilla, μm	377.98	351.70	393.60	402.62	14.497	0.184	0.235
Width of the top of the papilla, μm	413.01	377.13	362.17	397.92	13.149	0.644	0.830
Papilla height, μm	2326.57	2087.16	2246.04	1849.14	122.589	0.165	0.092
ELPS ⁶ , μm	864.22	854.24	879.19	813.13	39.196	0.585	0.855
Muscle tunic thickness, μm	1261.43	1128.68	1235.53	1152.32	55.583	0.535	0.829

¹ Concentration of CMA in the dry matter of the diet. ² Standard error of the mean. ³ Linear regression.

⁴ Quadratic regression. ⁵ Match the average percentage of injury observed in the animals in the treatment.

⁶ Thickness of the lamina propria-submucosa.

3.1.2. N-Ammonia and Short-Chain Fatty Acid Profile

The ruminal N-ammonia concentration of the lambs did not show a significant difference ($p > 0.05$) between the different CMC doses. There were also no significant differences

($p > 0.05$) in the profiles of SCFAs, such as acetic acid, propionate, isobutyrate, butyrate, isovaleric, and valeric, of the lambs submitted to the different treatments (Table 3).

Table 3. Ammonia nitrogen concentration and short-chain fatty acid (SCFA) profile in the rumen of lambs confined in the growing and finishing phase receiving different doses of the clayey trace mineral compound.

Variables	Treatments (% in DM) ¹				EPM ²	<i>p</i> -Value	
	0.00	0.40	0.80	1.20		<i>L</i> ³	<i>Q</i> ⁴
NH ₃ -N, mg/dL	12.58	8.54	6.08	7.17	1.244	0.116	0.142
Acetic acid, mg/dL	106.73	101.02	113.31	113.38	4.038	0.387	0.683
Propionate acid, mg/dL	68.47	59.07	66.42	66.00	4.269	0.985	0.910
Isobutyrate acid, mg/dL	0.93	0.65	0.93	0.65	0.069	0.326	0.621
Butyrate acid, mg/dL	34.88	35.54	30.10	32.47	1.906	0.502	0.752
Isovaleric acid, mg/dL	1.76	0.98	1.58	1.25	0.128	0.423	0.568
Valeric acid, mg/dL	2.94	2.22	2.46	2.34	0.171	0.341	0.450

¹ Concentration of CMA in the dry matter of the diet. ² Standard error of the mean. ³ Linear regression.

⁴ Quadratic regression. NH₃-N: rumen ammonia nitrogen.

3.2. Blood Count and Biochemical Examination

Among the blood parameters for the biochemical examination and blood count, there was only a significant difference ($p < 0.05$) between the treatments for the aspartate amino-transferase (AST) variable, with a higher concentration in the non-supplemented lambs (control treatment) (107.17 U/L) and a lower value in the lambs that received the highest CMC dose (95.17 U/L) (Table 4). The other variables did not show significant differences between the treatments ($p > 0.05$).

Table 4. Blood count and blood biochemistry parameters of lambs confined in the growing and finishing phase receiving different doses of the clayey trace mineral compound (CMA) in the diet.

Variables	References ¹	Treatments (% in DM) ²				EPM ³	<i>p</i> -Value	
		0.00	0.40	0.80	1.20		<i>L</i> ⁴	<i>Q</i> ⁵
Complete Blood Count								
Cell volume, %	-	34.50	34.00	32.17	34.17	0.666	0.726	0.553
Prothrombin time, s	6–7	6.13	5.93	5.90	5.83	0.064	0.113	0.240
Fibrinogen, cells/μL	300–600	466.67	366.67	400.00	400.00	32.923	0.614	0.683
Red blood cells, cells/μL	10–14	14.11	13.52	13.39	12.96	0.300	0.188	0.419
Hemoglobin, g/dL	8–14	12.37	12.07	11.85	12.18	0.281	0.809	0.821
Leukocytes, cells/μL	4–12	9.64	9.60	9.71	10.17	0.507	0.703	0.913
Monocyte cells/μL	0–750	252.83	473.33	486.50	373.67	66.706	0.610	0.402
Lymphocytes, cells/μL	2000–9000	4696.80	4467.23	4566.75	4964.30	297.262	0.711	0.937
Eosinophils, cells/μL	0–1000	69.87	0.00	43.27	40.60	18.182	0.823	0.706
Neutrophils, cells/μL	700–7000	4161.85	4623.42	4620.33	4733.02	346.170	0.603	0.846
PPT ⁶ , g/L	400–1000	735.83	509.50	769.83	631.17	50.906	0.881	0.966
Biochemical								
ALT ⁷ , U/L	5–45	11.50	13.50	11.33	8.50	1.137	0.251	0.346
AST ^{8, a} , U/L	41–298	107.17	89.00	91.50	95.17	2.747	0.230	0.057
Alkaline phosphatase, U/L	200–600	353.17	502.33	324.00	463.33	25.810	0.463	0.761
GGT ⁹ , U/L	25–150	85.67	69.50	68.83	80.50	3.756	0.752	0.168
Urea, mg/dL	10–92	31.67	26.67	34.67	29.00	1.271	0.923	0.932
Creatinine, mg/dL	0.6–1.7	0.95	0.88	0.85	0.85	0.025	0.150	0.261
Total protein, g/dL	3.1–10.7	6.07	5.57	6.05	5.93	0.087	0.906	0.702
Albumin, g/dL	1.1–5.2	3.68	4.34	3.68	3.75	0.142	0.760	0.750

^a Significant quadratic effect, $y = 105.80 - 1219.95x + 21143.58x^2$ $R^2 = 0.240$. ¹ Reference range for serum metabolites [36,37]. ² Percentage of addition of clay mineral compound (CMA). ³ Standard error of the average.

⁴ Linear regression. ⁵ Quadratic regression. ⁶ Total plasma protein. ⁷ Alanine aminotransferase. ⁸ Aspartate-aminotransferase. ⁹ Gamma-glutamylpeptidase.

3.3. Diet Consumption

The ADI data on the total diet, concentrate, and sugarcane (Table 5) did not show significant differences ($p > 0.05$) between the lambs in the control group and the lambs supplemented with CMC in the diet.

Table 5. Diet intake (based on DM) by lambs confined in the growing and finishing phase receiving different doses of the clay trace mineral compound (CMA) in the diet.

Variables	Treatments (% in DM) ¹				EPM ²	p-Value	
	0.00	0.40	0.80	1.20		L ³	Q ⁴
Total diet, g	1604.36	1781.21	1773.51	1769.15	48.932	0.306	0.379
Concentrate, g	608.85	660.96	648.61	647.10	8.889	0.242	0.160
Hydrolyzed sugarcane, g	995.50	1120.25	1124.90	1122.05	40.772	0.331	0.450
Crude protein, g/kg	150.25	149.77	139.56	143.40	0.379	0.405	0.651
Ether extract ^a , g/kg	29.44	32.41	33.36	30.51	0.051	0.524	0.004
Mineral matter, g/kg	21.68	28.33	23.06	17.76	0.154	0.178	0.084
Neutral detergent fiber ^a , g/kg	207.09	261.92	272.71	250.82	1.008	0.163	0.041
Acid detergent fiber, g/kg	23.97	65.03	55.03	42.77	0.629	0.512	0.087
Total carbohydrates ^a , g/kg	798.63	789.49	804.02	808.33	0.482	0.337	0.025
Non-fibrous carbohydrate, g/kg	591.53	527.57	531.31	557.52	0.940	0.310	0.532
Calcium (Ca), g/kg	10.71	14.14	16.44	6.47	0.185	0.431	0.139
Phosphorus (P), g/kg	7.25	7.22	7.21	7.23	0.010	0.939	0.989
Ratio C/P, g/kg	14.51	7.33	5.55	2.46	0.237	0.079	0.188

^a Significant quadratic effects for ether extract ($y = 2.94 + 30.02x - 577.26x^2$ $R^2 = 0.40$); neutral detergent fiber ($y = 20.86 + 459.71x - 7782.04x^2$ $R^2 = 0.27$); and total carbohydrates ($y = 79.64 + 18.61x + 959.45x^2$ $R^2 = 0.58$).

¹ Concentration of CMA in the dry matter of the diet. ² Standard error of the mean. ³ Linear regression.

⁴ Quadratic regression.

The same result was observed ($p > 0.05$) for the ADI data on crude protein (CP), mineral matter (MM), acid detergent fiber (ADF), non-fibrous carbohydrate (NFC), calcium (Ca), phosphorus (P), and the P/Ca ratio. However, a significant difference ($p < 0.05$) was observed for the ADI of ether extract (EE), neutral detergent fiber (NDF), and total carbohydrate (TC) (Table 5).

3.4. Animal Performance

The data on body measurements, such as body length, withers height, rump height, chest perimeter, rump width, and chest width, in centimeters, and performance, such as final weight, total weight gain, and ADG, in kilograms (Table 6), showed no significant differences between the treatments ($p > 0.05$).

Table 6. Body measurements and performance of lambs confined in the growing and finishing phase receiving different doses of the clayey trace mineral compound (CMA) in the diet.

Variables	Treatments (% in DM) ¹				EPM ²	p-Value	
	0.000	0.40	0.80	1.20		L ³	Q ⁴
Starting weight, kg	27.700	27.467	27.333	27.450	0.795	0.913	0.987
Final weight, kg	35.350	37.033	37.608	36.150	0.774	0.744	0.561
Total gain, kg	7.650	9.567	10.275	8.700	0.440	0.437	0.078
ADG, g/animal/day	0.139	0.174	0.187	0.158	0.008	0.435	0.076
Feed conversion, kg/kg	7.425	8.236	7.600	7.490	1.902	0.695	0.209
Feed efficiency, kg/kg	0.142	0.133	0.144	0.146	0.037	0.799	0.122
Body length, cm	63.167	63.000	63.667	62.833	0.675	0.930	0.961

Table 6. Cont.

Variables	Treatments (% in DM) ¹				EPM ²	p-Value	
	0.000	0.40	0.80	1.20		L ³	Q ⁴
withers height, cm	55.000	55.333	54.333	56.833	0.781	0.480	0.621
Croup height, cm	57.833	57.417	56.667	60.583	0.790	0.238	0.203
Chest circumference, cm	66.500	74.500	74.500	72.667	1.645	0.263	0.159
Croup width, cm	21.417	18.700	21.050	21.000	0.853	0.867	0.808
Chest width, cm	21.383	21.067	21.150	21.250	0.173	0.876	0.843

¹ Concentration of CMA in the diet. ² Standard error of the mean. ³ Linear regression. ⁴ Quadratic regression.

3.5. Yield and Quality Characteristics of the Carcass

There was no significant difference ($p > 0.05$) for any of the yield characteristics and biometric carcass measurements of the feedlot lambs, such as hot and cold carcass weight (HCW and CCW), hot and cold carcass yield (HCY and CCY), right and left carcass weight (RCW and LCW), and liquid loss by refrigeration after 24 h of cold storage at -4°C (Table 7).

Table 7. Yield and carcass quality characteristics of lambs confined in the growing and finishing phases receiving different doses of the clayey trace mineral compound (CMA) in the diet.

Variables	Treatments (CMA in MS%) ¹				EPM ²	p-Value	
	0.00	0.40	0.80	1.20		L ³	Q ⁴
Live weight at slaughter, kg	35.35	37.03	37.61	36.15	0.774	0.744	0.561
Right carcass weight, kg	8.65	8.67	8.83	8.70	0.203	0.886	0.967
Left carcass weight, kg	8.42	8.65	8.97	8.52	0.202	0.809	0.657
Hot carcass weight, kg	18.02	18.35	19.07	18.27	0.415	0.757	0.727
Hot casting yield, %	51.02	49.58	50.66	50.48	0.349	0.889	0.750
Cold carcass weight, kg	17.07	17.32	17.80	17.22	0.400	0.845	0.842
Cold casting yield, %	48.27	46.77	47.28	47.53	0.336	0.641	0.421
Loss from refrigeration, kg	0.95	1.04	1.27	1.06	0.075	0.500	0.420
Loss due to refrigeration, %	5.36	5.66	6.67	5.83	0.396	0.564	0.602
Leg circumference, cm	38.50	32.82	48.52	34.00	3.116	0.960	0.682
Neck weight, g	427.67	482.33	523.33	465.83	19.194	0.460	0.222
Pallet weight, kg	1.605	1.625	1.570	1.571	0.032	0.598	0.872
Rib weight, kg	2.696	2.626	2.724	2.619	0.077	0.830	0.967
Loin weight, kg	1.171	1.093	1.182	1.123	0.032	0.825	0.975
Leg weight, kg	2.772	2.805	2.838	2.802	0.062	0.853	0.941
Rib eye area, cm ²	17.66	17.53	16.27	16.21	0.389	0.115	0.287
Subcutaneous fat thickness, cm	1.76	1.65	2.21	1.94	0.110	0.312	0.509
Casting forming	3.3	3.0	3.4	3.3	0.090	0.432	0.722
Housing finish	3.2	3.3	3.8	3.2	0.110	0.825	0.178
Temperature at 0 h, °C	35.50	34.88	35.03	34.73	0.276	0.401	0.678
Temperature in 24 h, °C	11.37	12.62	11.30	12.33	0.460	0.685	0.923
pH at 0 h	7.10	6.92	6.83	6.90	0.045	0.128	0.091
pH in 24 h	5.88	5.87	6.04	5.88	0.037	0.725	0.471

¹ Concentration of CMA in the dry matter of the diet. ² Standard error of the mean. ³ Linear regression.

⁴ Quadratic regression.

There were also no significant differences in the yields of the five main cuts of the sheep carcass: neck, shoulder, shank, rib (whole), and loin. In addition, there was no statistical difference between the treatments in the values of LMA, SSE, carcass conformation, carcass finish, temperature, and pH at 0 h and 24 h.

3.6. Meat Quality

The meat quality characteristics showed significant differences between the treatments ($p < 0.05$) in an increasing linear regression for intensity of the variation from red to green color (a^*) and for color saturation (C^*) (Table 8). The values of a^* and C^* were directly proportional to the increase in the concentration of CMC in the diet. The other parameters, including meat color quality, brightness intensity (L^*), yellow/blue color intensity, and meat shade, did not show significant differences ($p > 0.05$) between the treatments. Likewise, the loss of liquid by cooking and shear force (tenderness) did not present significant results.

Table 8. Meat quality of lambs confined in the growing and finishing phase receiving different doses of the clayey trace mineral compound (CMA) in the diet.

Variables	Treatments (% in DM) ¹				EPM ²	p-Value	
	0.00	0.40	0.80	1.20		L^3	Q^4
L^*	39.194	41.911	39.927	39.518	0.583	0.800	0.500
a^*, a	15.586	15.577	17.793	17.691	0.428	0.026	0.083
b^*	5.003	5.446	5.888	5.488	0.285	0.518	0.588
C^*, a	16.461	16.565	18.760	18.567	0.423	0.026	0.076
H^*	0.351	0.379	0.344	0.323	0.024	0.564	0.786
Cooking loss, g	21.885	24.828	26.128	24.627	0.813	0.245	0.167
Cooking loss, %	20.069	21.544	21.081	18.940	0.694	0.480	0.376
Shear Force, N	2.403	2.210	2.155	1.822	0.145	0.161	0.379

^a Significant linear effect for: a^* red coordinate value ($y = 15.48 + 52.35x$ $R^2 = 0.205$); C^* color saturation coordinate value ($y = 16.42 + 51.98x$ $R^2 = 0.206$). L^* brightness intensity coordinate value; b^* yellow coordinate value; H^* the shade of the flesh; ¹ Concentration of CMA in the dry matter of the diet. ² Standard error of the mean. ³ Linear regression. ⁴ Quadratic regression.

3.7. Multivariate Analysis of the Significant Results

In the principal component analysis (PCA) of significant dependent variables ($p < 0.05$), all variables tended to cluster around the treatments with the highest CMC concentrations. The variables were positioned between the 0.80% and 1.20% CMC treatments (T3 and T4, respectively), showing an opposite pattern to the control (T0) and T1 (0.40%). The average daily intake (ADI) of total carbohydrates (TCs) was highly correlated with the 1.20% CMC treatment, whereas the ADI of NDF and EE showed strong correlations with the 0.80% CMC treatment (Figure 1).

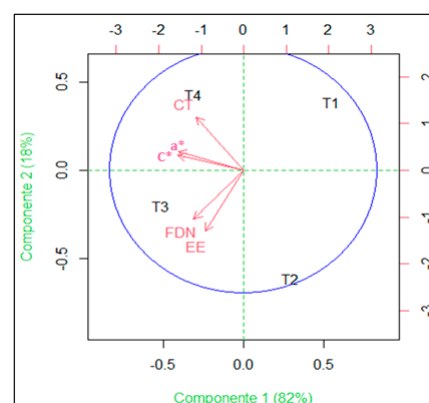


Figure 1. Principal component analysis of the dependent variables with significant values ($p < 0.05$). T1: without addition of clay micromineral compound (CMC); T2: 0.40% CMC in dry matter (DM); T3: 0.80% CMC in DM; T4: 1.20% CMC in DM; CT: average daily intake of total carbohydrates (g/kg); NDF: average daily intake of neutral detergent fiber (g/kg); EE: average daily intake of ether extract (g/kg); a^* : color coordinate representing the red-to-yellow variation in the longissimus muscle; C^* : color coordinate representing meat color saturation in the longissimus muscle.

Furthermore, the variables related to color coordinates—red to yellow variation (a^*) and color saturation (C^*)—in the longissimus muscle tended to associate with the higher CMC concentrations (T3 and T4), while disassociating from the lower concentrations (T1 and T2) (Figure 1).

4. Discussion

4.1. Morphological Evaluation of the Rumen

The CMC doses used in the lamb feed were not sufficient to cause significant effects on the ruminal lesion scores (Table 2). The use of CMC, such as bentonite, zeolite, and smectite, has been studied for its possible effects on the rumen metabolome [38,39]. Although hydrolyzed sugarcane and concentrate can cause rumen lesions, the CMC used did not have a significant effect. The short confinement time may have prevented the development of ruminal lesions.

Each CMC has specific mechanisms of action in the gastrointestinal tract. Bentonite has properties that can reduce rumen lesions and improve the efficiency of the rumen papillae, facilitating the absorption of SCFAs [40]. Montmorillonite has a high affinity for mycotoxins, acting by cation exchange [12,41]. Smectite, on the other hand, removes heavy metals from the rumen fluid, which also helps prevent injury [41].

The morphological and histological evaluations of the ruminal papillae showed non-significant results, confirming the findings for the lesion scores. The application of CMC in the appropriate proportion can benefit papillae development, but incorrect use can cause serious rumen damage [42]. The chemical structure of CMC directly influences the rumen epithelium, and inadequate concentrations can form an impermeable barrier that impairs the absorption of SCFAs [42,43].

Although Neubauer et al. [43] studied the effect of mineral clays on the microbiota of cows fed a high-concentrate diet, the results showed little effect on pro-inflammatory genes in the epithelium. More research is needed to better understand the effects of CMC on rumen epithelium.

4.2. N-Ammonia and SCFA Concentrations

The different CMC doses did not significantly affect ($p > 0.05$) the N-ammonia concentration in the ruminal fluid of the lambs. The amount of N-ammonia can be influenced by the high cation exchange capacity of clay minerals, such as aluminosilicates [44]. El-Nile et al. [13] observed that nano-zeolite reduced ($p < 0.001$) the $\text{NH}_3\text{-N}$ concentration in in vitro experiments. Another study on aflatoxin B1, bentonite, and *Saccharomyces cerevisiae* observed a reduction in $\text{NH}_3\text{-N}$ with the use of bentonite compared to a control treatment [15]. On the other hand, Aladdim He et al. [45] found an increase in the concentration of rumen ammonia in goats supplemented with bentonite.

The optimal range of $\text{NH}_3\text{-N}$ in the rumen is 15 to 20 mg/dL. Concentrations above this limit can impair rumen fermentation and feed digestibility [46,47]. On the other hand, low concentrations can reduce microbial activity and protein intake. Therefore, CMC can serve as a regulator, but the proper dosage must be known.

There were also no significant differences ($p > 0.05$) in SCFA concentrations (also known as VFA). However, several studies reported significant increases in SCFA concentrations, such as acetate, propionate, and butyrate, with the use of CMC. Aladdin He et al. [45] observed an increase in VFA concentration in goats supplemented with bentonite. Jiang et al. [15] also reported a significant increase in VFA concentration after 16 h of fermentation.

Gouda et al. [12] observed that bentonite and montmorillonite increased significantly ($p < 0.001$) VFA and $\text{NH}_3\text{-N}$ concentrations in goats. Although the results of the present

study did not show a significant effect with the doses tested, the CMC has the potential to increase SCFA intake in ruminants.

4.3. Lamb Blood Parameters: Blood Count and Biochemistry

The blood parameter analysis found that only aspartate aminotransferase (AST) showed a significant difference ($p < 0.05$) between the treatments. However, the AST concentrations stayed within the reference limits (41–298 U/L), indicating no evidence of hepatic alteration [36,37]. All other parameters remained within normal standards, indicating that the CMC doses tested did not cause negative effects in the lambs.

Research on the use of CMC and its effects on AST in ruminants is still limited. AST is an important enzyme in amino acid metabolism and in the assessment of liver and heart function [48]. In sheep, the hepatic concentration of AST is important to evaluate liver and cardiac functions, as both organs have a strong relationship with the concentration of this enzyme [49]. However, the AST concentration in this study showed a quadratic effect, with the lowest value for the intermediate dose (0.80% of CMC in DM), suggesting a maximum limit of addition.

Previous research on blood parameters of feedlot lambs is scarce. Azadbakht et al. [50] found no significant difference in parameters such as glucose and urea when evaluating bentonite supplementation in lambs. This corroborates the present results of the other blood count and biochemical parameters, all of which are within the parameters of normality, except AST, which requires further investigation, given the behavior of the data.

Gouda et al. [12] also observed that bentonite and montmorillonite did not affect the total protein, albumin, urea, and creatinine concentrations in goats. However, Aladdim He et al. [45] reported a significant increase in albumin concentration with the use of CMC, in addition to changes in the albumin/globulin ratio.

Although the CMC tested has a composition similar to bentonite, the doses used were lower for safety reasons, being a new product and little studied in ruminants.

4.4. Diet Consumption Data

The non-significant results for the ADI of the total diet, concentrate, and sugarcane indicate that the addition of the clayey mineral compound (CMC) does not harm the consumption of the animals. However, the significant increase in the consumption of ether extract (EE, $p < 0.004$) and neutral detergent fiber (NDF, $p < 0.041$) may suggest food selection by the animals. The increase in total intake, which includes indigestible fiber, raises doubts about this hypothesis. Few recent studies have investigated the impact of CMCs on consumption. Herdian et al. [51] observed that ewes supplemented with a mineral compound associated with probiotics had a reduction in concentrate ADI, without impairment in performance.

Studies on the use of mineral clay compounds (CMCs) in poultry indicate benefits for gut health, but there is little research on CMCs in ruminants, highlighting the need for more studies with beef sheep. Khalaf and Al-Gabi [11] did not find significant effects on NDF and EE ADI in lambs supplemented with bentonite, but they observed an increase in protein digestibility, which contrasts with the results of the present study.

4.5. Diet Acceptability

The acceptability of the diet, especially the concentrate with the CMC, was not affected, with the animals consuming it immediately. The low concentration of CMC and its minimal impact on organoleptic characteristics seem to justify this acceptability. Studies have shown no effects of CMCs on diet acceptability.

4.6. Animal Performance

There were no significant differences between the treatments in average daily gain (ADG), total gain (TWG), and final weight (FW), suggesting that the addition of the CMC does not impair performance. Toprak et al. [52] also observed that zeolite up to 2% did not affect ADG or FW of lambs. In another study, Hossein Yazdi et al. [53] reported a linear increase in ADG, FW, and ADI with the supplementation of a vitamin–mineral complex, showing that the combination of minerals and other additives may be more effective.

Khalaf and Al-Galbi [11] showed that bentonite improved nutrient digestibility and TWG, without affecting ADG. The authors suggested that bentonite reduces the rate of food passage by increasing nutrient absorption. This was also corroborated by Gouda et al. [12], who observed an increase in the production of volatile fatty acids in the rumen due to the higher digestibility of organic matter.

4.7. Body Measurements

No significant differences were observed in the body biometric measurements between the treatments. Few studies have evaluated these measures in sheep supplemented with CMC, but they are important for monitoring the growth and development of animals [54]. According to Gurgel et al. [55], measurements of thoracic circumference, abdomen, and rump height are highly correlated with body weight. Souza et al. [56] also found a high correlation between body volume and live animal weight. These measures can be used to analyze whether the development of lambs is within performance standards. The results of this research suggested that all the lambs grew according to the expected genetic patterns.

4.8. Quantitative and Qualitative Carcass Characteristics

The carcass yields did not show significant differences between the treatments. The results of the studies by Slamova et al. [57] show that the effect of CMCs can vary according to the dose and form of administration. Toprak et al. [52] reported that the addition of zeolite up to 2% did not affect carcass yield, but 3% reduced weight. Oliveira et al. [58] observed that bentonite and vermiculite improved meat quality but did not protect polyunsaturated fatty acids from rumen biohydrogenation.

Khalaf et al. [11] demonstrated that nano-bentonite improved carcass quality characteristics, with higher lean meat content and better muscle distribution. The comparison between CMCs and nanoparticles paves the way for future research, highlighting the potential of nanoparticles to improve the efficiency of additives.

4.9. Qualitative Characteristics of Meat

LMA, SSE, conformation, and carcass finish were not significantly influenced. Young-Jik et al. [5] also did not observe significant effects of bentonite on the centesimal composition and quality of meat in steers. Similar results were reported by Ossowski et al. [59] for pigs, where bentonite and zeolite improved the brightness of the meat, without altering the physicochemical properties.

In the present study, the highest CMC dose significantly increased red (a^*) and contrast (C^*) color, suggesting a direct relationship between the inclusion of the compound and these meat quality parameters. However, more studies are needed to determine the optimal CMC dose without compromising meat quality.

4.10. Multivariate Analysis

The principal component analysis showed a strong correlation between the higher-dose treatments (0.80% and 1.20% CMC) and nutrient intake (TC, NDF, and EE), in addition to staining (a^* and C^*). This relationship suggests that higher CMC doses may intensify

these effects, reinforcing the need for more research to understand the intensity of these correlations and their impacts on animal production.

Finally, some limitations of this study should be acknowledged, mainly due to the high experimental costs involved. This research was conducted with a limited sample size (24 lambs), using a single basal diet and evaluating only three inclusion levels of the clay-based micromineral compound, in addition to the control treatment. Nevertheless, as this represents a pioneering investigation using this type of mineral additive, the findings provide valuable information for future research. Additional studies with larger animal numbers and different feeding conditions are recommended to validate and expand the current evidence.

5. Conclusions

The CMC doses used in this experiment did not negatively affect the performance, health, or carcass and meat characteristics of feedlot lambs. Although some variables showed a trend toward improvement in nutrient use and meat quality, the beneficial effects were limited. The results indicate that CMC inclusion up to 1.2% can be considered safe, as no adverse effects were observed on blood parameters (hematological and biochemical) or rumen fermentation.

Based on these findings, we recommend that future studies evaluate higher inclusion levels of the compound to determine the maximum safe dosage without compromising animal performance or carcass quality. Additional research should also investigate the mode of action of clay-based nanoparticles and the potential synergistic effects of CMCs when combined with other feed additives. In summary, within the tested range, CMC supplementation appears safe but provides only modest productive benefits.

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Institutional Review Board Statement: The animal study protocol was approved by the Ethics Committee for Federal University of Goiás (protocol code 30/23 in 29 May 2023).

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