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# Performance, Body Composition, and Behavior of Lambs Consuming Different Extruded Roughage to Concentrate Ratios

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## ABSTRACT

**High levels of roughage in the diet reduce energy density and limit voluntary intake due to ruminal physical constraints. In this context, extrusion processing can improve digestibility and enable greater fiber inclusion in the diet, thereby improving animal performance. The objective of this study was to evaluate the productive performance, body composition, and ingestive behavior of lambs that were fed different proportions of extruded roughage to concentrate (R:C). Twenty lambs, weighing 25.0 ± 2.8 kg and aged 120 ± 8 d, were distributed in a completely randomized design and fed one of four proportions of roughage to concentrate: 30:70; 40:60; 50:50; or 60:40. Lambs were housed in collective pens throughout the experimental period. Body weight (BW) and body condition score (BCS), body conformation (in vivo biometric measurements), average daily gain (ADG, g/d), and in vivo carcass characteristics were not influenced by the treatments (p>0.05). An increase in roughage levels linearly increased total chewing time (TCT) (p<0.05). In contrast, idle time (IT) decreased linearly (p<0.05). There was a quadratic and positive linear effect of evaluation day (p<0.05) for BW, BCS, in vivo biometric measurements, ADG during the periods between 15–30 d (p=0.03) and 75–90 d (p<0.05), and in vivo carcass characteristics (p<0.05). There was an interaction between R:C ratio and the day of assessment for loin eye area, with day 84 superior to day 0 (p<0.05). The inclusion of higher levels of roughage in fully extruded diets increases TCT and decreases IT without affecting productive performance or body composition in sheep.**

***Keywords:*** *body biometrics; chewing; extrusion; fiber; weight gain*

## INTRODUCTION

Diets with high roughage content limit ruminant performance mainly by increasing ruminal fill and reducing energy density, thereby restricting voluntary intake and nutrient utilization. However, the extrusion process improves ruminal microorganism access to nutrients because the combined action of heat, pressure, and shear forces alters the physical structure of the feed, breaking down cell walls and modifying fiber and starch organization, which enhances digestibility, nutritional value, and facilitates forage handling and storage (Assis *et al*., 2022; Oliveira *et al*., 2020), thus promoting this technique as a promising strategy for fiber utilization in ruminant nutrition.

In modern and intensive sheep production systems, the inclusion of high levels of concentrates has been a common practice to maximize energy intake and daily weight gain (Li *et al*., 2021). Nevertheless, this approach may lead to selective feeding behavior by animals that increases labor and management costs. In this context, the extrusion of the aerial parts of grasses emerges as an innovative strategy to enable the inclusion of higher proportions of roughage in the diet without compromising animal performance.

Studies indicate that extrusion can significantly improve nutrient digestibility (Abadi *et al*., 2023; Amirteymoori *et al*., 2021), increase intake (Silva *et al*., 2020; Silva *et al*., 2021; Siqueira *et al*., 2022), and enhance the efficiency in animal production (Li *et al*., 2021; Zhang *et al*., 2019). Consequently, the inclusion of extruded roughage in ruminant diets allows a more efficient adjustment of the roughage-to-concentrate ratio while meeting energy requirements and ruminal physical constraints (Oliveira *et al*., 2019a; Oliveira *et al*., 2019b). Despite these advances, limited information is available regarding the maximal level of roughage inclusion in fully extruded diets for growing lambs. To date, most studies evaluating extruded feeds in sheep have focused on partial inclusion of extruded ingredients or on performance outcomes alone, without simultaneously addressing ingestive behavior and carcass traits under



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fully extruded dietary systems (Assis *et al*., 2022; Oliveira *et al*., 2025; Ribeiro *et al*., 2025; Silva *et al*., 2023).

This study investigated the effects of different roughage levels in fully extruded diets for growing sheep by evaluating the diet's influence on animal performance, nutrient utilization efficiency, ingestive behavior, and carcass traits. We hypothesized that diet extrusion would allow higher roughage inclusion without impairing nutrient intake, growth performance, or carcass traits while simultaneously increasing chewing and rumination time through physical modification of fiber structure during extrusion.

## MATERIALS AND METHODS

### Location, Animals, Experimental Design, and Diets

The study was approved by the Ethics Committee on Animal Use of the Federal University of Uberlândia (UFU), protocol number 094/17, and conducted at the Small Ruminant Sector (UFU) located in Uberlândia, Minas Gerais, Brazil, at an altitude of 863 m (coordinates: 18°87′79.6″ S, 48°34′46.9″ W). The experimental period was characterized by an average temperature of 17.4 °C, relative humidity of 64.02%, and no precipitation.

Twenty intact male lambs with a genetic background of ½ Dorper × ½ Santa Inês, an initial body weight (BW) of 25.0 ± 2.8 kg, 120 ± 8 d of age, and dewormed orally with levamisole and monepantel were assigned to a completely randomized design and housed in collective pens (20 m²) with slatted floors. The pens were in a covered masonry barn equipped with a drinker, a feeder with a headlock design, and a mineral feeder. Although animals were housed in collective pens, all variables, including performance, ingestive behavior, and carcass traits, were measured individually; therefore, the individual animal was considered the experimental unit in the statistical analyses. Each pen housed five animals for 105 d, with the first 15 d used for adaptation to the pens and diets, followed by 90 d of data collection.

Fully extruded diets were used with four roughage-to-concentrate (R:C) ratios: 60:40; 50:50; 40:60; and 30:70 (Tables 1 and 2). The roughage (aerial part of sugarcane – *Saccharum officinarum* – plus starch, minerals, and urea) and the concentrate (corn meal, sorghum meal, urea, soybean meal, monensin, mycotoxin adsorbent, and sheep mineral premix) were pelleted separately by the industry and subsequently mixed according to the proportions described above. The composition and proportions of the products' ingredients were kept confidential due to commercial patent protection. Owing to the heterogeneous composition of the total ration at the time of feeding, additional manual homogenization was performed directly in the feeder to avoid preferential selection of roughage or concentrate by the animals and to ensure uniform access to the diet components.

Food was provided twice daily at 08:00 h and 16:00 h, with 50% of the total daily food allowance offered at each feeding. Animals were fed ad libitum, allowing

Table 1. Chemical composition of feed ingredients for lambs

| Nutrients, % DM[1] | Feeds | |
|---|---|---|
| | Extruded roughage | Extruded concentrate |
| Dry matter | 91.00 | 92.48 |
| Mineral matter | 4.70 | 5.73 |
| Organic matter | 95.3 | 94.27 |
| Crude protein | 7.70 | 18.77 |
| Neutral detergent fiber | 47.80 | 15.24 |
| Acid detergent fiber | 35.20 | 10.85 |
| Ether extract | 2.00 | 1.39 |
| Total digestible nutrients | 70.89* | 81.43** |

Note: [1]Information provided by the manufacturer; analyses performed at the 3R Ribersolo Laboratory – Central of Agricultural Intelligence for High-Precision Diagnostics; *TDN = 87.84 – (0.7 x %ADF) (Rodrigues, 2010); **TDN = 93.53 – (1.3 x %ADF) (Rodrigues, 2010).

Table 2. Chemical composition of fully extruded experimental diets with different roughage-to-concentrate ratios for lambs

| Nutrients, % DM[1] | Roughage-to-concentrate ratios of the diets | | | |
|---|---|---|---|---|
| | 30:70 | 40:60 | 50:50 | 60:40 |
| Dry matter | 92.04 | 91.89 | 91.74 | 91.59 |
| Mineral matter | 5.42 | 5.32 | 5.22 | 5.11 |
| Organic matter | 94.58 | 94.68 | 94.78 | 94.89 |
| Crude protein | 15.45 | 14.34 | 13.24 | 12.13 |
| Neutral detergent fiber | 23.41 | 26.89 | 30.38 | 33.86 |
| Acid detergent fiber | 16.59 | 19.25 | 21.91 | 24.56 |
| Ether extract | 1.57 | 1.63 | 1.70 | 1.76 |
| Total digestible nutrients* | 73.96 | 70.51 | 67.05 | 63.60 |

Note: [1]Data obtained at the Laboratory of Bromatology and Animal Nutrition of the Federal University of Uberlândia through analysis of samples collected during the experiment; *TDN = 93.53 – (1.3 x %ADF) (Rodrigues, 2010).

refusals ranging from 5 to 10% of the total feed offered. Refusals on an as-fed basis were used to adjust the daily amounts offered due to the high dry matter content of the feeds in their natural form (Table 2). Water and mineral salt were provided *ad libitum* to the animals.

### Data Collection

BW, growth, and body condition score (BCS) of the animals were recorded at 15-d intervals, beginning with the first day after the 15-d adaptation period. BCS was assessed by palpation of the $12^{th}$ and $13^{th}$ lumbar vertebrae, allowing the evaluation of fat deposition in the animal: 1 – very thin; 2 – thin; 3 – normal; 4 – fat; 5 – obese (Russel *et al*., 1969). A single trained evaluator conducted all BCS evaluations to minimize subjectivity.

Subcutaneous fat thickness (SFT), height, and length of the *longissimus dorsi* muscle, for calculation of the loin eye area (LEA) according to McManus *et al*. (2013), were evaluated by *in vivo* carcass ultrasonography at the beginning (day 0) and at the end (day 84) of the experiment, using a Mindray DP 2200 device after trichotomy of the measurement area between the $12^{th}$ and $13^{th}$ lumbar vertebrae. Both evaluations were performed at 08:00 h after animal restraint to avoid errors during image acquisition, and the images were processed immediately after collection.

To assess body growth, in vivo biometric measurements were obtained using a measuring tape after restraining the animals on a flat surface, allowing proper alignment for the description of: barrel circumference (BC) of the lower part of the ribs where the flank is located; thoracic circumference (TC) at the posterior region of the scapulae near the axillae; rump height (RH) = the vertical distance between the highest point (in the direction of the ilium bone) and the ground; withers height (WH) = the vertical distance between the highest point (in the direction of the scapula) and the ground; chest width (CW) = the distance between the lateral faces of the scapulohumeral joints on the right and left sides; body length (BL) = the distance between the base of the tail (ischial bone) and the base of the neck (lateral face of the scapulohumeral joint).

Ingestive behavior was evaluated at the beginning of the experiment and at 30-d intervals and expressed as the mean result of four observations. Animals were observed by six trained observers for a total of 24 h at 5-min intervals to determine solid feed intake, water and mineral salt intake, rumination, and idling (Oliveira *et al*., 2024). Total chewing time was defined as the sum of the times spent on solid feed intake and rumination. During the nighttime period, the environment received artificial lighting, which was kept on for 5 d before evaluation to promote animal adaptation to artificial light conditions.

Intra-observer reliability was assessed using data obtained from five 5-min videos randomly selected from lambs participating in the study. In these videos, the frequency of each behavior was recorded twice by the same observer on different occasions. To evaluate intra-observer reliability, the intraclass correlation coefficient (ICC) was calculated using a two-way model, with an absolute agreement definition and single-measure statistics (Harvey *et al*., 2016; Koo & Li, 2016). ICC values range from −1 to 1 (complete disagreement to excellent agreement, with zero indicating agreement no better than chance) (Hallgren, 2012). The ICC was 0.941 (95% CI: 0.900–0.965), indicating excellent reliability of the observer's assessments (Koo & Li, 2016). The F-test confirmed that the agreement was significantly different from zero ($p<0.05$), reinforcing the robustness of the evaluations. The analysis was performed in R using the irr package.

### Statistical Analysis

The study was conducted as a completely randomized design, with four treatments varying in R:C ratio, each with five replicates. The individual animal was considered the experimental unit for all evaluated variables, despite collective housing. Animal was included as a random effect in the statistical model, while the R:C ratio and time (repeated measures over time) were treated as fixed effects and tested for linear or quadratic effects. When both linear and quadratic effects were significant within the same evaluation, the equation with the highest $R^2$ was used as the criterion for selecting the best model.

Data were tested for normality (Shapiro–Wilk test) and homogeneity of residual variances (Levene's test) using the SAEG 9.1 software. Variables with normal distribution and homogeneous variances were subjected to analysis of variance, and means were compared using Tukey's test at a significance level of $p\leq0.05$.

## RESULTS

Dietary dry matter (DM) decreased progressively from 92.04% to 91.59% as the forage proportion increased from 30% to 60% (Table 2). A similar pattern was observed for nutritional attributes, including mineral matter (MM; 5.52% to 5.11%), crude protein (CP; 15.45% to 12.13%), and total digestible nutrients (TDN; 75.83% to 72.04%). Consequently, a higher proportion of dietary forage increased the contents of organic matter (94.58% to 94.89%), neutral detergent fiber (NDF; 23.41% to 33.86%), acid detergent fiber (ADF; 16.59% to 24.56%), and ether extract (EE; 1.57% to 1.76%).

There was no effect ($p>0.05$) of R:C ratio on BW, BCS, or body conformation (in vivo biometric measurements) of the animals (Table 3). However, a quadratic effect of evaluation day was observed ($p<0.01$) for BW, BC, TC, CW, and BL. Despite the exponential growth pattern, these measurements became stabilized toward the end of the experimental period. In contrast, BCS, RH, and WH showed a positive linear effect ($p<0.01$) throughout the entire experimental period (Table 4).

The ADG of lambs was not affected by the R:C ratio over the total evaluation period ($p>0.05$). However, a quadratic effect was observed during the 15–30-d period ($p=0.03$). ADG increased as the concentrate proportion decreased (241.33, 263.33, and 315.00 for ratios 30:70, 40:60, and 50:50, respectively), then declined at 40%

forage inclusion in the diet (86.66). A negative linear effect was observed during the 30–45-d period (p=0.01), with ADG increasing concomitantly with the reduction of concentrate in the R:C ratio. Conversely, a positive linear effect was observed during the 75–90-d period (p<0.01), in which ADG decreased concomitantly with an increase in forage proportion in the R:C ratio (Table 5).

No effect of the different R:C ratios on the carcass characteristics evaluated by in vivo ultrasonography was observed (p>0.05; Table 6). There was a significant (p<0.05) increase in subcutaneous fat thickness (SGT) and in base and height measurements (used to calculate LEA) on day 84. At the end of the study, base, height, and SGT were 5.73, 5.10, and 0.80 mm greater, respectively, compared with the beginning of the experiment.

There was an interaction between the R:C ratios and the evaluation period for LEA, with LEA being higher on day 84 than on day 0 (baseline) across all diets (p<0.01; Table 7). At the end of the study, the 30:70, 40:60, 50:50, and 60:40 ratios showed increases of 3.62, 2.69, 1.87, and 2.59 mm, respectively, compared to values at the beginning of the experiment. However, there was no effect of increasing dietary forage proportion on LEA across evaluation days.

Increased forage levels linearly increased (p<0.01) the time spent in TCT, which rose from 391 to 544 min/d as the R:C ratios increased from 30:70 to 60:40 (Table 8).

Table 3. Body weight, body condition score, and *in vivo* body biometrics of sheep fed fully extruded diets with different forage-to-concentrate ratios

| Variables | Forage-to-concentrate ratio | | | | CV (%) | p-value |
|---|---|---|---|---|---|---|
| | 30:70 | 40:60 | 50:50 | 60:40 | | |
| BW, kg | 31.08 | 32.80 | 34.20 | 36.60 | 14.59 | 0.81 |
| BCS | 3.08 | 3.08 | 3.21 | 3.21 | 11.98 | 0.85 |
| BC, cm | 77.71 | 80.85 | 83.25 | 86.25 | 8.02 | 0.31 |
| TC, cm | 68.92 | 71.26 | 72.51 | 73.08 | 9.08 | 0.63 |
| WH, cm | 57.92 | 56.54 | 57.71 | 59.88 | 6.91 | 0.62 |
| RH, cm | 57.45 | 56.97 | 57.14 | 59.34 | 7.01 | 0.76 |
| CW, cm | 18.69 | 19.04 | 19.88 | 20.77 | 10.04 | 0.10 |
| BL, cm | 57.50 | 57.54 | 58.20 | 59.42 | 6.19 | 0.87 |

Note: BW= body weight; BCS= body condition score; BC= barrel circumference; TC= thoracic circumference; WH= withers height; RH= rump height; CW= chest width; BL= body length; CV= coefficient of variation (%).

Table 4. Body weight, body condition score, and *in vivo* body biometrics of sheep fed fully extruded diets with different forage-to-concentrate ratios at different evaluation times

| Variables | Day of evaluation | | | | | | | CV (%) | p-value |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 15 | 30 | 45 | 60 | 75 | 90 | | |
| BW, kg | 21.30[c] | 25.60[bc] | 30.16[b] | 33.11[b] | 37.11[ab] | 40.98[a] | 44.06[a] | 14.79 | <0.01[1] |
| BCS | 2.84[c] | 3.02[b] | 3.25[ab] | 3.20[ab] | 3.00[b] | 3.15[ab] | 3.52[a] | 12.73 | <0.01[2] |
| BC, cm | 70.31[c] | 74.68[bc] | 81.68[b] | 81.72[b] | 85.13[ab] | 88.31[a] | 90.54[a] | 8.22 | <0.01[3] |
| TC, cm | 61.59[c] | 65.13[c] | 69.27[bc] | 73.09[b] | 74.72[b] | 76.04[ab] | 79.40[a] | 9.26 | <0.01[4] |
| WH, cm | 54.22[b] | 55.59[b] | 55.27[b] | 58.09[a] | 59.86[a] | 60.68[a] | 61.90[a] | 7.57 | <0.01[5] |
| RH, cm | 54.22[b] | 55.50[b] | 56.09[b] | 57.59[ab] | 59.18[a] | 60.04[a] | 61.13[a] | 7.17 | <0.01[6] |
| CW, cm | 15.68[b] | 16.72[b] | 19.00[ab] | 19.59[ab] | 21.13[a] | 21.54[a] | 23.04[a] | 10.48 | <0.01[7] |
| BL, cm | 51.86b | 53.77b | 57.09[ab] | 59.22[ab] | 59.81[ab] | 62.18[a] | 62.81[a] | 6.96 | <0.01[8] |

Note: [1]$Y= 21.343723 + 0.301223x - 0.000546x^2$. $R^2= 0.99$; [2]$Y= 2.921266 + 0.004924x$. $R^2= 0.53$; [3]$Y= 70.607143 + 0.327381x - 0.001219x^2$. $R^2= 0.97$; [4]$Y= 61.522727 + 0.284416x - 0.001025x^2$. $R^2= 0.99$; [5]$Y= 53.896104 + 0.090043x$. $R^2= 0.96$; [6]$Y= 54.155844 + 0.078355x$. $R^2= 0.99$; [7]$Y= 15.598485 + 0.105087x - 0.000272x^2$. $R^2= 0.98$; [8]$Y= 51.648268 + 0.192532x - 0.000753x^2$. $R^2= 0.99$; BW= body weight; BCS= body condition score; BC= barrel circumference; TC= thoracic circumference; WH= withers height; RH= rump height; CW= chest width; BL= body length; CV= coefficient of variation (%); Means in the same row with different superscripts differ significantly (p<0.05).

Table 5. Average daily gain of sheep fed fully extruded diets with different forage-to-concentrate ratios (g $day^{-1}$)

| Period (days) | Forage-to-concentrate ratio | | | | CV (%) | p-value |
|---|---|---|---|---|---|---|
| | 30:70 | 40:60 | 50:50 | 60:40 | | |
| 0 – 15 | 175.33 | 129.58 | 94.16 | 146.67 | 35.36 | 0.25 |
| 15 – 30 | 241.33[b] | 263.33[ab] | 315.00[a] | 86.66[c] | 38.45 | 0.03[1] |
| 30 – 45 | 153.33[c] | 125.00[c] | 241.66[b] | 325.33[a] | 47.96 | 0.01[2] |
| 45 – 60 | 242.66 | 228.33 | 280.00 | 198.33 | 32.42 | 0.25 |
| 60 – 75 | 157.33 | 210.00 | 171.66 | 207.33 | 39.56 | 0.36 |
| 75 – 90 | 191.33[a] | 168.33[a] | 175.02[a] | 102.00[b] | 44.40 | <0.01[3] |
| 0 – 90 | 175.33 | 170.55 | 187.77 | 145.44 | 22.30 | 0.88 |

Note: [1]$Y= - 1148.0774775 + 60.449693x - 0.625849x^2$. $R^2 = 0.83$; [2]$Y= 496.0325 - 6.32665x$. $R^2= 0.81$; [3]$Y= - 28.4322 + 3.61331x$. $R^2= 0.73$; CV= coefficient of variation (%); Means in the same row with different superscripts differ significantly (p<0.05).

Table 6. *In vivo* carcass ultrasonography of sheep fed fully extruded diets with different forage-to-concentrate ratios at different evaluation times

| Variables | Forage-to-concentrate ratio | | | | Day of evaluation | | CV (%) | p-value | |
|---|---|---|---|---|---|---|---|---|---|
| | 30:70 | 40:60 | 50:50 | 60:40 | 0 | 84 | | F:C | Day |
| Base, mm | 39.41 | 38.73 | 39.39 | 40.70 | 36.50[b] | 42.23[a] | 4.55 | 0.64 | <0.01 |
| Height, mm | 26.51 | 26.00 | 27.17 | 25.94 | 23.84[b] | 28.94[a] | 6.64 | 0.85 | <0.01 |
| SGT, mm | 2.17 | 1.97 | 1.69 | 1.87 | 1.54[b] | 2.34[a] | 12.58 | 0.51 | <0.01 |

Note: SGT= subcutaneous fat thickness; CV= coefficient of variation (%); Means in the same row with different superscripts differ significantly (p<0.05).

Table 7. Interaction between loin eye area (LEA) and evaluation period in sheep fed fully extruded diets with different forage-to-concentrate ratios

| Period (days) | Forage-to-concentrate ratio | | | | p-value |
|---|---|---|---|---|---|
| | 30:70 | 40:60 | 50:50 | 60:40 | |
| 0 | 6.53[b] | 6.64[b] | 7.50[b] | 6.92[b] | 0.10 |
| 84 | 10.15[a] | 9.33[a] | 9.37[a] | 9.51[a] | 0.12 |
| p-value | <0.01 | <0.01 | <0.01 | <0.01 | |

Note: Means in the same row with different superscripts differ significantly (p<0.05).

Table 8. Ingestive behavior of sheep fed fully extruded diets with different forage-to-concentrate ratios

| Activities, min day$^{-1}$ | Forage-to-concentrate ratio | | | | CV (%) | p-value |
|---|---|---|---|---|---|---|
| | 30:70 | 40:60 | 50:50 | 60:40 | | |
| Intake | 170 | 180 | 171 | 195 | 21.53 | 0.32 |
| Rumination | 221 | 268 | 269 | 349 | 29.32 | 0.63 |
| Total chewing | 391[b] | 448[b] | 440[b] | 544[a] | 19.14 | <0.01[1] |
| Idle time | 1049[a] | 992[a] | 1000[a] | 896[b] | 8.59 | <0.01[2] |

Note: [1]Y= 254.95 + 4.42333x. $R^2$= 0.78; [2]Y= 1186.65 – 4.503333x. $R^2$= 0.82; CV= coefficient of variation (%); Means in the same row with different superscripts differ significantly (p<0.05).

In contrast, an opposite pattern was observed for idle time, which decreased linearly (p<0.01) as dietary forage increased. Idle time ranged from 1,049 to 896 min/d when the forage proportion in the diets doubled from 30% to 60%.

## DISCUSSION

The increase in dietary roughage associated with reduced idle time and similar body performance among all diets reinforces the role of extrusion in modifying fiber structure and stability during digestion, indicating that this processing technique enables greater fiber inclusion in diets for growing lambs without impairing productive performance, as previously reported for meal-type diets (Parente *et al*., 2016). Physically processed, pelleted, or extruded diets markedly reduce particle selection compared with non-processed diets (Abadi *et al*., 2023), which is corroborated by our observations.

Extrusion reduces particle selection by altering fiber length, density, and the cohesion among dietary components, resulting in a more homogeneous feed matrix and limiting the animals' ability to consume concentrate fractions selectively (Oliveira *et al*., 2019b; Oliveira *et al*., 2025; Zhang *et al*., 2019). This reduction in sorting behavior has been directly quantified in sheep through lower refusals of fine or coarse particles and reduced variability in nutrient intake among animals (Li *et al*., 2021; Nascimento *et al*., 2020). This uniformity of intake is beneficial for animal performance, as it ensures a balanced distribution of essential nutrients for growth and body development (Ding *et al*., 2016; Dougherty *et al*., 2022). Moreover, by maintaining fiber integrity and preventing selective intake, extrusion contributes to a more stable ruminal environment, improving digestive efficiency and nutrient absorption, as evidenced by studies reporting improved feed efficiency and ruminal fermentation profiles in lambs fed extruded diets (Li *et al*., 2021; Oliveira *et al*., 2020; Zhang *et al*., 2019).

Thus, the results of our study demonstrated the relationships among the proportion of roughage in the lambs' diets, fiber content (NDF and ADF), and TCT. Initially, increasing the proportion of roughage resulted in a significant increase in fiber content, with higher NDF and ADF values due to the greater proportion of structured plant material rich in fibrous components. The higher fiber content in the diets directly affected the feeding behavior of the lambs, particularly TCT, since fiber requires more chewing time to be adequately broken down and prepared for ruminal digestion.

Despite significant changes in fiber content and chewing behavior, BC, although related and potentially indicative of intake capacity and abdominal expansion (Oliveira *et al*., 2020), did not follow the same pattern. Fiber in larger particles leads to ruminal wall distension and, consequently, an increase in BC. However, the fiber particle size of approximately 2 mm resulting from extrusion appears to have prevented excessive ruminal fill, which is important for increasing dry matter intake (Oliveira *et al*., 2024; Rodrigues *et al*., 2022; Siqueira *et al*., 2022).

This result suggests that variation in diet composition did not perceptibly affect the animals' body conformation. The maintenance of BC may indicate that, although fiber content and chewing time increased, total nutrient and energy intake were sufficient to sustain uniform body growth (Dougherty *et al*., 2022; Oliveira *et al*., 2020). Thus, even with variation in the R:C ratio, the diets were nutritionally adequate to support the lamb's body development.

BCS followed a positive linear trend throughout the study, as the animals stabilized muscle growth and began to deposit fat. Differences in the growth rates of muscle, bone, and adipose tissues are observed due to physiological maturity (Ponnampalam *et al*., 2024). Studies such as that by Hicks *et al*. (2021) show that bone tissue exhibits early growth, followed by intermediate muscle growth, and finally by later adipose tissue growth. In summary, muscles tend to develop more rapidly in young animals, whereas fat deposition becomes more pronounced after complete body development. In addition to physiological maturity, diet composition can influence the efficiency and extent of fat deposition in growing sheep (Dougherty *et al*., 2022). Diets with higher energy density, particularly those with increased levels of digestible carbohydrates or lipids, have been associated with enhanced adipose tissue deposition and different carcass fat patterns (Dougherty *et al*., 2022; Ponnampalam *et al*., 2024). Conversely, diets with higher fiber content but lower energy density may limit the efficiency of energy partitioning toward fat storage, even as animals reach later growth stages (Ding *et al*., 2016). Therefore, the energy concentration and nutrient balance of the diet play important roles in determining the pattern and efficiency of fat deposition during the finishing phase of lamb growth.

Lambs follow a sigmoidal growth curve, characterized by a slow initial phase, acceleration until puberty, and stabilization at maturity (Silva *et al*., 2024). During early growth, muscle tissue deposition predominates, but as animals mature, fat deposition becomes more prominent. This shift reflects the progressive approach to physiological maturity in which hormonal regulation redirects nutrient partitioning from lean tissue accretion toward adipose deposition, a process that is largely independent of short-term dietary variations (Bell *et al*., 1987). This transition is crucial for subcutaneous fat thickness, which is fundamental to producing high-quality meat (Shao *et al*., 2024). Therefore, animals subjected to the different treatments in our study exhibited consistent growth, suggesting that although diet may play a role in tissue deposition efficiency, the overall growth pattern is strongly influenced by intrinsic biological factors, such as genetics and maturity, as well as feeding management.

The observed increase in SFT and length and height of the *longissimus dorsi* muscle, as well as BCS and overall body development of the animals during the experimental period, can plausibly be attributed to the transition to the pubertal phase. The significant increase in the length of the *longissimus dorsi* muscle recorded on day 84 reflects homogeneous growth in both length and height, indicating overall body development of the animals. The increase in muscle height may be related to adjacent bone growth, which provides structural support for the growing muscle, particularly at its base (Silva *et al*., 2024). These findings highlight the relevance of puberty in the morphological development of the animals and its potential influence on body composition and muscle development during the evaluation period.

Oliveira *et al*. (2019a) demonstrated that increasing dietary energy concentration is directly associated with increases in LEA and, consequently, with the amount of muscle in the carcass, showing a positive correlation between these traits. Therefore, LEA is frequently used as an indicator of carcass composition (McManus *et al*., 2013). Thus, it was expected that the animals had a larger LEA at the end of the experimental period since the extruded feed consumed is characterized by higher digestibility and fermentability of nutrients (Oliveira *et al*., 2020), including proteins, carbohydrates, and fibers, with TDN values above 70%, indicating high energy availability (Table 2).

Short-term fluctuations in ADG throughout the experimental period were likely associated with dietary adaptation and inherent physiological growth phases. During the initial stages of exposure to fully extruded diets with varying roughage levels, animals may undergo transient adjustments in intake patterns and ruminal function, which can temporarily influence growth rates (Oliveira *et al*., 2019a; Oliveira *et al*., 2025). As adaptation progresses, ADG tends to stabilize and increasingly reflects the natural growth trajectory associated with advancing age and proximity to maturity, rather than solely direct dietary effects.

Throughout the experiment, we observed that even with an increase in the proportion of roughage in the diet, from 30% to 60%, the animals maintained a similar LEA. This suggests that, in addition to the extrusion process of the roughage improving fiber digestion, diets with higher roughage proportions can achieve similar gains due to greater energy availability from the diet's higher TDN values (Table 2). These results highlight the advantage of including extruded roughage in animal diets, as it allows increasing the proportion of this component without compromising LEA or, consequently, carcass composition.

Despite the consistency of responses across treatments, our study had limitations. The experimental duration and sample size, although sufficient to detect differences in ingestive behavior and carcass-related traits, may have limited the detection of subtle treatment effects on short-term growth dynamics, particularly during early dietary adaptation. In addition, the evaluation period did not extend to slaughter, which restricts inferences regarding final carcass yield and commercial cut composition.

From a practical perspective, the results indicate that fully extruded diets with roughage inclusion levels of up to 60% can be successfully applied in feedlot or semi-intensive sheep production systems without compromising animal performance or carcass development. The reduction in idle time and maintenance of carcass traits suggests improved feeding efficiency and potential benefits for labor management and feed utilization. These findings support the adoption of extruded roughage as a strategy to increase dietary fiber intake while maintaining productive efficiency, thereby enabling more flexible, potentially cost-effective feeding programs for growing sheep.

## CONCLUSION

Increasing the proportion of roughage in fully extruded diets increases mastication time. It reduces idle time without affecting productive performance or body composition of sheep, allowing a greater proportion of extruded roughage in the ration. Thus, roughage:concentrate ratios between 60:40 and 30:70 can be used without deleterious effects on the animals. From a practical standpoint, these findings support the use of fully extruded diets as a viable strategy in feedlot and semi-intensive sheep systems, enabling greater dietary flexibility, improved feed management, and potential reductions in feeding costs without compromising animal performance.

## CONFLICT OF INTEREST

We certify that there is no conflict of interest with any financial, personal, or other relationships with other people or organizations related to the material discussed in the manuscript.

## DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

We certify that generative artificial intelligence and/or AI-assisted technologies were not used in the writing of this manuscript, nor in the analysis, interpretation of data, or preparation of figures and tables.

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