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Performance, carcass traits and meat quality of lambs fed with different roughage: concentrate ratios associated with variable physically effective neutral detergent fibre content

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Abstract

This study evaluated the effect of roughage:concentrate (R:C) ratio associated with a variable particle size of physically effective neutral detergent fibre (peNDF8) in the forage (Tifton-85 hay) on the performance, carcass traits and meat quality of lambs. Seventy-two 4-month-old, non-castrated Santa Ines male lambs (23.5 ± 2.32 kg BW) were distributed in a completely randomized design, in a 2 × 2 factorial arrangement [two peNDF8 hay particle sizes (13 and 6 mm) and two R:C ratios (700:300 and 500:500 g/kg DM total)]. DMI, DM, NFC and TDN digestibility's, N-intake and N-faecal excretion were affected by the R:C ratio ($P < 0.05$). However, the N-retained was not affected by the studied variables ($P > 0.05$). It was observed an interaction ($P < 0.05$) between the peNDF8 and R:C ratios for final BW, average daily gain (ADG), colour parameters and pH 24 h. The lower roughage ratio provided greater ($P < 0.05$) concentrations of C14:1, C16:1–*cis*9, C18:1–*cis*9, ΣMUFA, Σ*n*–*6*:Σ*n*–*3* and hypocholesterolemic/hypercholesterolemic index, enzymatic activity Δ9desaturase-C16 and -C18. Lambs fed a lower roughage diet had improved performance and feed efficiency, however, presented reduced polyunsaturated fatty acids (PUFA) concentrations in the meat, especially Σ*n*–*3* family. Higher roughage diet and larger peNDF8 particle size improved the concentrations of PUFA while decreased Σ*n*–*6*:Σ*n*–*3* ratio in meat. Larger peNDF8 particle size associated with higher roughage proportion, have reduced animal performance however, it increased protein concentration, a* and C* colour parameter without affecting fatty acids profile of *Longissimus lumborum* muscle.

Introduction

The eating habits of meat consumers have become increasingly demanding, not only seeking for safer and higher-quality food, but also healthier (Arruda *et al*., 2012; Gesteira *et al*., 2018). Understanding the attributes that define the quality of the meat becomes extremely important in order to meet consumer demands while expanding livestock markets. The *Longissimus lumborum* has been used as a model for meat quality attributes since it can predict the acceptance of meat by the consumer market while analysing its parameters such as colour, shear force and fatty acid (FA) profile as they respectively represent the appearance, tenderness and deposition of intramuscular fat in the meat. These parameters can be decisive in choosing the product by the consumer (Costa *et al*., 2018).

Under specific dietary management, ruminants can change the amount of fat deposited and the FA composition of the meat thereafter. Mistakenly, the general FA profile is associated with an increase in the incidence of cardiovascular diseases and atherosclerosis which somewhat is likely to affect consumer perception of meat products (Parodi, 2016; Ribeiro *et al*., 2018). Concomitantly, there has been a growing interest in finding appropriate and natural ways to positively manipulate the FA composition of red meat in order to minimize the risks to human health (Wood *et al*., 2008; Parodi, 2016; Gesteira *et al*., 2018; dos Santos *et al*., 2019).

Diets with high energy density, as is the case of high concentrate diets, improve animal performance and promote greater deposition of fat, which can in turn cause a variation in

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Table 1. Physically effective neutral detergent fibre (peNDF) of Tifton-85 hay processed in screen with different diameters using Penn State Particle Separator (PSPS) fed to lambs receiving two proportions of peNDF and two roughage:concentrate (R:C) ratios

	Diameter of hay processing screen	
Variables	13 mm	6 mm
g/kg DM retained in screen		
19 mm	816	551
8 mm	22.7	42.2
1.18 mm	94.7	31.1
Base	66.3	96
peNDF		
Physically effective (pe_8)	0.84	0.59
Physically effective ($pe_{1.18}$)	0.93	0.9
peNDF8 (g/kg DM)	641	453
peNDF 1.18 (g/kg DM)	713	691

DM, dry matter; pe8, particles larger than 8.0 mm; pe1.18, particles larger than 1.18 mm.

the meat composition (Santos-Silva *et al.*, 2002; Araújo *et al.*, 2017). However, several studies have demonstrated that by increasing the amounts of concentrate in finishing diets, the proportion of saturated fatty acids (SFA) in the meat also increases (dos Santos *et al.*, 2019), which is not a desirable trait for health-concerned consumers. In contrast, other studies have shown that higher levels of roughage in ruminant diets promote increased deposition of Σ*n–3* polyunsaturated fatty acids (PUFA) in the muscle due to higher levels of linolenic acid (C18:3) found in forages (Realini *et al.*, 2004; Wood *et al.*, 2008).

In addition, there is limited information regarding the variability of the physically effective neutral detergent fibre content and its influence on the content of FA deposited in the carcass of meat-type lambs.

Though it is more difficult to optimize animal performance with forage-based backgrounding only, in the rumen, a consequential reduction in retention time will reduce the biohydrogenation performed by rumen microorganisms on dietary PUFA, hence decreasing fat toxicity to rumen microbes and consequently increasing the incorporation of these FA into the meat (Wood and Enser, 1997). Previous studies have demonstrated that physically effective fibre affects apparent nutrient digestibility, chewing activity, among other performance traits of which all are big players in determining retention time (Wang *et al.*, 2017). Thus, it is hypothesized that strategically exploring the amount of physically effective NDF (peNDF) from the larger peNDF8 (13 mm) particle size ruminant diets provide a better substrate for microorganisms, contribute to the maintenance of fermentation patterns and stability of the rumen environment and consequently it may improve the performance, fat deposited in *Longissimus lumborum* muscle, as well as the physicochemical and lipidic quality of meat. Then, this research was carried out to evaluate the effect of roughage:concentrate (R:C) ratio associated and variable particle size of peNDF8 in the forage (Tifton-85 hay) on the performance, carcass traits and meat quality of lambs.

Materials and methods

Location

The experiment was conducted at the São Gonçalo dos Campos Experimental Farm of the Federal University of Bahia (São Gonçalo dos Campos, Bahia, Brazil).

Animals, diets, management and experimental design

Seventy-two Santa Inês intact male lambs, with an average age of 100 ± 10 days and initial average body weight (BW) of 23.5 ± 2.32 kg, were used in this study. Animals were individually housed in stalls (1.0 × 1.0 m) with slatted wood floors, provided with individual water and feed troughs. The experiment lasted 85 days being 15 days for adaptation to the environment, management procedures and diets, and the remaining 70 days for performance evaluation.

Samples from dietary ingredients and refusals were collected weekly and then frozen (−20°C) for posterior chemical analysis. The lambs were fed a total mixed ration (TMR) composed of Tifton-85 hay as a roughage source, and a concentrate containing: maize bran, soybean meal, urea a mineral mixture. Diets were formulated to be isonitrogenous with 16% of CP according to NRC (2007) recommendations for an average daily gain (ADG) of 200 g, and inherently, had different amounts of non-fibrous carbohydrates (NFC; 232 and 348 g/kg for 700:300 and 500:500, respectively). The animals were fed a TMR, which was supplied twice per day, at 07:00 and 15:00 h, allowing 10% of refusals (as fed basis). After a period of 24 h, the refusals were collected, weighted, and the intake was adjusted. Additionally, the ingestion of dry matter and other nutrients by the animals was recorded.

The Tifton-85 hay was ground in a forage chipper daily, and separated by two sieves with different diameters (13 or 6 mm) in order to account for variation in forage particle size (Table 1). Then the hay was separated again using the Penn State Particle Separator – PSPS (Pennsylvania, U.S. Department of Agriculture; Harrisburg, PA, USA) to estimate the peNDF. The peNDF was calculated in two ways according to the size of the hay particles: peNDF8, which is the sum of the percentages of the particles larger than 8.0 mm (Lammers *et al.*, 1996), and peNDF1.18, which is the sum of the percentages of the particles larger than 1.18 mm (Kononoff *et al.*, 2003). Additionally, the peNDF was calculated by multiplying the NDF content of the sample by the predetermined peNDF according to Mertens (1997). The processing with the different sieves did not change the content for peNDF1.18, but it did however for peNDF8, obtaining final values of 641 g/kg DM for 13 mm particles, and 453 g/kg for 6 mm particles. Thus, it was used as a treatment for the size particles observed: peNDF1.18 = 6 mm and peNDF8 = 13 mm.

The lambs were distributed in a completely randomized design following a 2 × 2 factorial arrangement of treatments accounting two particles size (13 mm and 6 mm) of peNDF8, and two the R:C ratios (700:300 and 500:500 g/kg DM total). The treatments were: 13 mm of peNDF8 sized at 700:300 g/kg DM of R:C ratio, 6 mm of peNDF8 sized at 700:300 g/kg DM R:C ratio, 13 mm of peNDF8 sized at 500:500 g/kg DM R:C ratio and 6 mm of peNDF8 sized at 500:500 g/kg DM of R:C ratio.

Chemical composition of the diet

Triplicate samples of ingredients, diets, refusals and faeces were pre-dried at 55°C for 72 h, ground into a knife mill (Tecnal,

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Table 2. Ingredient proportions, chemical and fatty acids composition of the ingredients and experimental diets of lambs fed with two proportions of physically effective neutral detergent fibre (peNDF8) of Tifton-85 hay content and two roughage:concentrate (R:C) ratios

	Ingredients		
Chemical composition (g/kg DM)	Tifton 85 hay	Maize bran	Soybean meal
Dry matter (g/kg as fed)	870	836	856
Crude protein	98.1	91.0	486
Ether extract	11.6	44.7	27.2
NDF corrected for ash and protein	699	153	108
Acid detergent fibre	380	21.5	60.1
NDIP[A] (g/kg CP)	524	183	30
ADIP[A] (g/kg CP)	105	16.8	3
Non-fibrous carbohydrates	117	695	306
Acid detergent lignin	51.5	22.5	23.6
Ingredient proportions in diets (g/kg DM)	Roughage:concentarte ratio (g/kg DM)		
	700:300		500:500
Tifton-85 hay	700		500
Maize bran	171		370
Soybean meal	104		105
Urea	10		10
Mineral mixture	15		15
Chemical composition (g/kg DM)			
Dry matter (g/kg as fed)	866		859
Crude protein	163		162
Ether extract	44		50.8
NDF corrected for ash and protein	527		417
Acid detergent fibre	276		204
NDIP[A] (g/kg CP)	248		206
ADIP[A] (g/kg CP)	46.6		36.1
Non-fibrous carbohydrates	232		348
Acid detergent lignin	42.4		36.6
Fatty acids composition g/100 g FAME from identified fatty acids			
C12:0	0.67		0.49
C14:0	0.85		0.65
C16:0	34.4		33.3
C16:1 cis9	0.23		0.24
C18:0	4.8		5.59
C18:1 cis9	8.67		17.8
C18:2 cis9 cis12	23.7		22
C18:3 cis9 cis12 cis15	19.2		12.7
Others	7.43		7.31

DM, dry matter; NDIN, neutral detergent insoluble nitrogen; ADIN, acid detergent insoluble nitrogen; CP, crude protein; FAME, fatty acid methyl esters.

Piracicaba City, São Paulo State, Brazil) to pass a 1 mm sieve, then stored in airtight plastic containers (ASS, Ribeirão Preto City, São Paulo State, Brazil). Laboratory analyses (Table 2) were performed according to the Association of Official Analytical Chemists (AOAC, 2012) for: dry matter (DM, method 930.15), crude protein (CP, method 2001.11), ether extract (EE, method 2003.05) and crude ash (method 942.05).

The NDF content was determined according to Van Soest *et al.* (1991) not assayed with heat-stable α-amylase and expressed as inclusive of residual ash. Acid detergent fibre (ADF) contents were determined as described by Robertson and Van Soest (1981). The ADF residue was treated with 72% sulfuric acid (AOAC, 2012) to determine acid detergent lignin. The NDF residue was incinerated at 600°C for 4 h, and analysed for CP getting neutral detergent fibre corrected for ash and protein (NDF_{ap}). The neutral detergent insoluble nitrogen and acid detergent insoluble nitrogen values were obtained following the recommendations of Licitra *et al.* (1996). The non-fibre carbohydrates (NFC) content was determined as proposed by Mertens (1997): NFC = 100–NDFap–CP–EE–ash.

Intake, digestibility, nitrogen balance and microbial synthesis efficiency

During the experimental period, refused feed was collected and weighed each day to determine daily intake.

Samples of faeces and urine were collected between days 60 and 67 of the experimental period, using 20 lambs (five lambs from each treatment). For the collection of faeces, appropriate canvas bags were attached to the animals using nylon strips to minimize the disruption to the lambs. Then, between the 54th and 67th days (14 days in total, seven for adaptation and seven for faeces collection), 4 g of titanium dioxide (TiO_2) indicator were offered daily, per animal. The TiO_2 was mixed in the concentrate of the 20 lambs, in order to determine the consumption of concentrate. The TiO_2 was quantified following the methodology described by Myers *et al.* (2004).

The digestibility coefficients (DC) of DM, CP, EE, NDFap and NFC were calculated as follows: DC = [(kg of the fraction ingested–kg of the fraction excreted)/(kg of the fraction ingested)] × 100. The intake of total digestible nutrients (TDN) was calculated according to Sniffen *et al.* (1992), and the dietetic concentrations of TDN were calculated from the following equation: TDN = (TDN intake/DM intake) × 100.

Total urine collection was performed using a funnel and a plastic container in each lamb with 100 ml of 20% sulfuric acid to keep the urine pH below 3.0, and at the end of each collection the samples were filtered with the aid of gauze and their total volume measured. An aliquot of 50 ml of urine was stored and then 10 ml of urine was diluted in 40 ml of 0.036N sulfuric acid solution (Valadares *et al.*, 1999), which were packed in identified plastic bottles and stored at −20°C for further analysis.

The nitrogen (N) contents of triplicate samples of the provided diet, faeces and urine were determined according to AOAC (2012) method 981.10. The body balance (retention) of N (N retained, g/d) was obtained using N-balance (g/d) = N-intake (g/d)–[N-excreted in the faeces (g/d) + N excreted in the urine (g/d)].

An aliquot of urine collected urine was filtered, and a 10 ml sample was diluted with 40 ml of stock solution (0.018 mM H_2SO_4) and stored at −20°C for subsequent analyses of xanthine, hypoxanthine, allantoin and uric acid. Analysis of xanthine, hypoxanthine and allantoin was conducted by a colourimetric

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method (Chen and Gomes, 1992). Uric acid was analysed according to Fossati *et al.* (1980).

The quantity of absorbed microbial purines (X, mmol/day) was calculated from the excretion of purine derivatives (Y, mmol/day) using the following equation (Chen and Gomes, 1992): $Y = 0.85X + 0.385 \times BW^{0.75}$, where 0.85 is the recovery of purines absorbed as purine (AP) derivatives in urine and $0.385 \times BW^{0.75}$ represents the endogenous contribution to purine excretion. The microbial synthesis of nitrogenous compounds in the rumen was estimated as a function of the absorbed purines and the N_{RNA}:N_{TOTAL} ratio in the microorganisms (Chen and Gomes, 1992): N-microbial production = $(70 \times AP)/(0.83 \times R \times 1000)$, where Nmicr is the microbial nitrogen flow in the small intestine (g/day), R is the N_{RNA}:N_{TOTAL} ratio in the microorganisms (mg/mg), 70 is the nitrogen content in purines (mg/mol), and 0.83 is the intestinal digestibility of the microbial purines (mg/mg). The microbial synthesis efficiency (g Nmicr/100 g TDN) was determined by dividing the microbial protein production by the TDN intake.

Blood samples were collected from all animals from the jugular venipuncture in the morning before feeding on experimental day 30. Disposable needles (25 mm × 8 mm) were used, and 10 ml blood samples were placed in glass tubes without anticoagulant for biochemical tests. The blood serum was centrifugated at 2000 × g for 10 min in a refrigerated centrifuge (Centrilab® model CE3001, São Paulo, Brazil) and separated (in duplicate) from the cell pellet using a Pasteur pipette (Centrilab®, São Paulo, Brazil). Blood urea nitrogen (BUN) were analysed with the following methods (Labtest® Diagnostic SA, Minas Gerais, Brazil).

Performance, slaughtering procedure and obtaining the Longissimus lumborum muscle

The lambs were weighed at the beginning and at the end of the experiment, always in the morning after 16 h of fasting. At the end of the experimental period, the final body weight (FBW) was obtained. It was also calculated by the total weight gain (TWG), through the difference between FBW and the initial BW, and the ADG, by dividing the results by the number of days of feedlot. The feed efficiency (g/g) was calculated as the ratio between the ADG and dry matter intake (DMI). At the end of the experimental period, the animals, which were approximately 7 months old, were fasted for 24 h and weighed for the determination of shrunk BW at slaughter. Lambs were harvested in a commercial packing plant following guidelines of the Brazilian Federal Inspection Service (Brazil, 2000). Animals were stunned by electronarcosis (220 V, 1.5 A for 10 s), suspended by the hind limbs, and exsanguinated by the section of jugular veins and carotid arteries.

Skinning was performed after the removal of the head and legs, and evisceration was followed by inspection of the viscera by qualified technicians. After the described procedures, the carcasses were transferred to a cold chamber and kept in the chamber at 4°C for 24 h. After this period, the carcasses were weighed again for the determination of the cold carcass weight (CCW) from which the commercial yield of the carcass (CCY = CCW/HCW × 100) was determined.

The carcasses were sectioned longitudinally into two hemi carcasses and samples were obtained from the *Longissimus lumborum* muscle. Loin eye area (LEA) was measured by drawing its area on a transparency film and final area was integrated into a leaf area reader (LI 3100, Li-corinc). The subcutaneous fat thickness (SFT) was measured using a digital caliper.

Physicochemical composition of the meat

The pH was evaluated 24 h after slaughter in the *Longissimus lumborum* using a Mettler M1120x pH meter (Testo, 205 Gerate-Set, Lenzkirch, Alemanha). Next, an average was calculated, and this average was considered the pH value of the muscle.

Cooking weight loss (CWL) of the *Longissimus lumborum* muscle was performed in two samples that were 2.5 cm thick. The weight of the samples was recorded before and after cooking. The samples were trimmed off of subcutaneous fat and cooked on an electric grill (George Foreman Jumbo Grill GBZ6BW, Rio de Janeiro, Brazil). A stainless-steel thermocouple (Gulterm 700, Gulton do Brasil) was placed into the geometric centre of each sample to check and record the internal temperature. The samples were cooked until the internal temperature reached 71°C. Next, the samples were removed from the grill, placed into a plastic bag and cooled to 10°C using an ice-water bath. The CWL of each sample was obtained by the weight difference before and after sample cooking. Samples were equilibrated at 4°C overnight for instrumental texture analysis conducted according to the methods of AMSA (2015).

Warner–Bratzler shear force (WBSF) was measured by a texture analyser (Texture Analyser TX-TX2, Mecmesin, Nevada, USA) fitted with a Warner–Bratzler type shear blade with a load of 25 kg*f* and a cutting speed of 20 cm/min according to Shackelford *et al.* (1999). Prior to WBSF analysis, samples were brought to room temperature. At least three muscle cores parallel to the muscle fibres, 1.27 cm diameter by 2.0 cm length, were removed from each sample using a cork borer. Each core was sheared perpendicularly to the fibre direction.

The meat colour was evaluated using a transverse cut of muscle that was exposed to atmospheric air for 30 min before reading the oxygen myoglobin, which is the primary element that defines meat colour (Hunt and King, 2012). After 30 min, as described by Miltenburg *et al.* (1992), the coordinates L*, a* and b* were measured at three different points in the muscle in non-overlapping zones, and an average was calculated for each coordinate. These measurements were performed using a Minolta colourimeter (Konica Minolta, Chroma Meter CR 410, Tokyo, Japan) that was previously calibrated with the CIELAB colour system using a blank tile, illuminate D65 and 10° as the standard observation points. L* is related to lightness (L* = 0 black, 100 white); a* (redness) where samples would range from green (−) to red (+); and b*(yellowness) where samples would range from blue (−) to yellow (+). The colour saturation (chroma index or C*) was calculated by the formula $C^* = (a^{*2} + b^{*2})^{0.5}$, according to Hunt and King (2012).

Determination of moisture, ash and CP were performed using a near-infrared spectrophotometer (FoodScan, FOSS NIRsystems Inc., Laurel, MD) according to Anderson (2007).

Fatty acid profile

To determine the FA profile, the lipids previously extracted from the *Longissimus lumborum* muscle and diets (Table 2) were converted to fatty acid methyl esters (FAME) according to Christie (1982). The FAME were prepared using a solution of methanol, ammonium chloride and sulphuric acid, following the procedure described by Hara and Radin (1978).

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Samples were then homogenized and centrifuged at 1000 g for 5 min, followed by aspiration of the top layer. Samples were then evaporated to zero moisture under nitrogen purging to avoid oxidation. Next, 0.5 ml of 0.5 M NaOH in methanol was added into the tube, homogenized and heated for 5 min at 100°C. Boron trifluoride is added at 0.5 ml in 14% methanol, homogenized and heated for 5 min at 100°. One ml of saturated salt solution and another of hexane is then homogenized with the sample. Then samples are centrifuged at 1000×*g* for 5 min and the hexane layer is separated which contains the FAME derivatized according to the methods described by Folch *et al.* (1957).

The FAME were determined in triplicate using a gas chromatograph (Finnigan Focus model, Varian, Palo Alto, CA, USA) equipped with a flame ionization detector and a capillary column (CP-Sil 88, 100 m × 0.25 mm i.d. × 0.20 µm film thickness, Varian, Palo Alto, CA, USA). Hydrogen was used as the carrier gas at a flow rate of 1.8 ml/min. The initial oven temperature was set to 70°C for 4 min, increased by 13°C/min to 175°C and held for 27 min; then increased by 40°C/min to 215°C and held for 9 min; and increased for 7°C/min to 230°C and held for another 9 min for a total of 65 min per sample. The injector temperature was set at 250°C, and the detector temperature was set at 300°C.

The quantification of the methyl esters of FA was based on the normalization of the area, the samples and the standard were injected into the chromatograph together with an internal standard (Supelco TM Component FAME Mix, cat 18919 Supelco, Bellefonte, PA, USA). The FAME were identified by a comparison of its retention time and those of authentic standards (FAME Mix, C4-C24, SIGMA-ALDRICH, St. Louis, USA). To quantify the FAME, a response factor was generated for each FA based on the standard, and the response factor of each FA was obtained. The results were quantified by normalizing the areas of the methyl esters and are expressed as g/100 g of FAME.

The sum (Σ) of the total SFA (ΣSFA), monounsaturated fatty acids (ΣMUFA), PUFA (ΣPUFA) and the desirable fatty acids (ΣDFA), ΣPUFA: ΣSFA, and Σn–6: Σn–3 ratios were calculated from the FA composition. To evaluate the nutritional quality of the lipid fraction of the meat samples, the atherogenicity index (AI) and thrombogenic index (TI) were calculated according to the equation (Ulbricht and Southgate, 1991): $AI = [(C12 + 4 \times C14 + C16)/(\Sigma MUFA + \Sigma n\text{–}6 + \Sigma n\text{–}3)]$; $TI = (C14 + C16 + C18)/[0.5 \times \Sigma MUFA + 0.5 \times \Sigma n\text{–}6 + 3 \times /(\Sigma n\text{–}6)]$. The hypocholesterolemic and hypercholesterolemic (h/H) FA ratio was calculated as h/H = [(ΣC18:1 *cis–9*, C18:2 *n–6*, C20:4 *n–6*, C18:3 *n–3*, C20:3 *n–6*, C20:5 *n–3* and C22:6 *n–3*)/(ΣC14:0 and C16:0)] (Arruda *et al.*, 2012).

Enzymatic activities of Δ^9desaturase (C16 and C18) and elongase were determined using the mathematical model described by Malau-Aduli *et al.* (1997) according to the following equations: Δ9dessaturase–C16 = 16:1*cis–9*/(16:0 + *cis–9* 16:1); Δ9dessaturase–C18 = 18:1*cis–9*/(18:0 + 18:1*cis–9*); and elongase index = 100 [(C18:0 + C18:1*cis–9*)/(C16:0 + C16:1*cis*–9 + C18:0 + C18:1*cis*–9)].

Statistical analysis

Data were analysed according to a completely randomized design, in a 2 × 2 factorial arrangement, to account for peNDF8 hay particle size (13 and 6.0 mm) and the R:C ratio (700:300 and 500:500 g/kg DM total). The following mathematical model was used:

$$Yij = m + \alpha i + \beta j + \alpha\beta ij + eij$$

where Y is the observed value of the ij variable that refers to the repetition of the combination of the i-th level of physically effective fibre with the j-th level of R:C ratio; m is the overall mean of all experimental units to the variable; αi is the effect of the i-th level of physically effective fibre of the observed value Yij; βj is the effect of the j-th level of roughage: concentrate ratio of observed value Yij; $\alpha\beta\ ij$ is the effect of the interaction between the i-th level of physically effective fibre and the j-th level of the R:C ratio; and eij is the error associated with the Yij observation.

The data were submitted to the analyses of outliers through the studentized residual, data points were removed if the studentized residual was outside the range of −2.5 to 2.5. Data were also tested for normality by the Shapiro–Wilk's test and homogeneity of variance by the LEVENE's test. The initial weight was used as a co-variable and kept in the model only when deemed significant. The data were subjected to an analysis of variance, followed by Tukey's test using the PROC MIXED of SAS (SAS 9.1 Institute, 2014). The means were adjusted (LSMEANS – Least Square Means) and significance was declared at $P < 0.05$.

Results

There was a significant interaction (Table 3) between the peNDF8 particle size and R:C ($P > 0.05$), as well as of the peNDF8 particle size individually ($P > 0.05$) on the DMI and DC (Table 3). Lambs presented greater DMI ($P < 0.001$) when fed with more concentrate (700 g/kg DM). The R:C ratio affected the digestibility of diets, with higher DC for DM ($P = 0.033$), NFC ($P < 0.001$) and TDN ($P < 0.001$), when there was a higher proportion of concentrate in the diet.

The amount of N-urinary excreted was affected ($P < 0.05$) by the interaction between the tested factors, so the averages of the split are shown in Table 4. There was an effect ($P = 0.032$) of the change in the R:C ratio in diets with hay processed with a 13 mm diameter sieve, and the N-urinary excretion of 3.5 g with the addition of concentrate in the diet from 30 to 50%. Another effect of the interaction ($P < 0.05$) was the diameter of the hay processing sieve in the diets with a 700:300 ratio, and the reduction in the particle size of the roughage increased the N-urinary (3.4 g).

The reduction in the peNDF8 particle size did not change ($P > 0.05$) in the N balance. The R:C ratio presented an effect ($P < 0.05$) in the N-intake and the amount of N-faecal excreted and consequently, there was an effect on the amount N-absorbed, also in BUN and N-microbial production. Microbial efficiency was not affected by the treatments.

The lambs fed diets with 700 g/kg DM roughage ingested 6.34 g less of N than 500 g/kg DM. N-faecal excretion increased (2.15 g) with the increase in the proportion of concentrate in the diet. Regarding the N-absorbed, the lambs that received the diet with a 500:500 ratio, despite having excreted a greater amount of N, also had a higher N-intake, making the amount of N available to be absorbed greater. BUN was higher in lambs that received diets with 700 g/kg roughage. N-microbial production was higher (6.80 g/d) for animals fed with a higher proportion of concentrate (700 g/kg DM).

There was a significant interaction (Table 5) between the peNDF8 particle size and R:C for final BW ($P = 0.032$), TWG ($P = 0.032$), ADG ($P = 0.033$) and feed efficiency (ADG:DMI ratio; $P < 0.001$), pH 24 h ($P < 0.001$), a* ($P = 0.022$) and C* ($P = 0.025$). Despite of observed lower final BW for lambs fed higher roughage proportion (700 g/kg) in the diet, decreasing

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Table 3. Digestibility, nitrogen (N) balance and microbial synthesis efficiency of lambs fed with two proportions of physically effective neutral detergent fibre (peNDF8) of Tifton-85 hay content and two roughage:concentrate (R:C) ratios

	$_{pe}NDF_8$ size of hay and R:C ratio					*P* value		
	13 mm		6 mm					
Items	700:300	500:500	700:300	500:500	SEM	peNDF8	R:C	peNDF8 × R:C
Dry matter intake (kg/d)	1.06	1.16	1.02	1.21	0.023	0.343	<0.001	0.073
Digestibility								
DM	0.7	0.7	0.7	0.7	0.89	0.543	0.033	0.362
CP	0.7	0.7	0.7	0.7	0.90	0.545	0.325	0.658
NDF	0.6	0.6	0.6	0.6	0.10	0.542	0.731	0.930
NFC	0.8	0.8	0.8	0.9	0.85	0.540	<0.001	0.971
TDN	0.7	0.7	0.7	0.7	0.89	0.511	<0.001	0.401
Nitrogen balance (g/d)								
N-intake	30	30	27	33	1.1	0.911	<0.001	0.660
N-faecal	8.4	8.6	7.4	9.6	0.36	0.743	<0.001	0.991
N-urinary	13.1	14.1	13.0	14.2	0.55	0.272	0.232	0.032
N-absorbed	22.1	21.7	19.8	24.0	0.94	0.774	0.016	0.596
N-retained	9.2	8.0	7.4	9.8	0.78	0.433	0.133	0.445
BUN[3]	24.2	22.4	24.9	21.6	0.50	0.053	<0.001	0.502
N-mic. Prod.[2]	5.5	5.9	4.6	6.8	0.40	0.503	<0.001	0.992
MicSE[4]	7.0	7.5	7.0	7.5	0.37	0.502	0.512	0.621

SEM, standard error of the mean; DM, dry matter; CP, crude protein; NDF, neutral detergent fibre; NFC, non-fibrous carbohydrates; TDN, total digestible nutrients; N-mic. Prod., N-microbial production; BUN, blood urea nitrogen (mg/dl); MicSE, microbial synthesis efficiency (g N/100 g TDN).

Table 4. Unfolding of interaction between the tested factors for nitrogen urinary excretion (g/day) of lambs fed with two proportions of physically effective neutral detergent fibre (peNDF8) of Tifton-85 hay content and two roughage:concentrate (R:C) ratios

		peNDF8 size of hay				
Variable	R:C ratio (g/kg DM)	13 mm	6 mm	SEM	*P* value peNDF8	*P* value R:C
N-urinary excretion (g/d)	700:300	11	15	1.3	0.020	0.389
	500:500	14.8	13.6	0.95	0.023	0.023

SEM, standard error of the mean.

particle size (13 to 6 mm) and $_{pe}NDF_8$ (641–453 g/kg) promoted an increase in FBW, TWG, ADG and ADG:DMI. Within the same particle sizes, lower roughage proportions have shown performance improvements from the TWG, ADG and ADG:DMI. When lambs were fed diets with lower roughage proportion, neither particle size nor peNDF8 has demonstrated improvements on any performance nor carcass traits. Decreasing particle size only affected lambs fed lower roughage proportion, with an observed increase of pH 24 h after slaughter and a decrease in redness (a*) and colour saturation (C*) of the meat. For lambs fed the higher roughage diet, particle size did not seem to affect pH 24 h, a* or C* of the *Longissimus lumborum*. However, higher roughage proportion for (700:300 R:C ratio) with larger peNDF8 size (13 mm) was similar at lower roughage proportion and 6 mm size.

Additionally, by decreasing peNDF8 size of hay (13 to 6 mm), it was observed an increase (3.08 kg) in final BW for the diet's roughage. By increasing the proportion of concentrate in the diet, we observed that higher peNDF8 size of hay (13 mm) did not affect final BW ($P = 0.059$; 38.1 *v.* 39.3 kg, for 700:300 and 500:500 g/kg of roughage, respectively). The peNDF8 and particle size did not affect carcass traits ($P > 0.05$), however, R:C ratio did ($P < 0.001$). Decreasing the roughage proportion in the diet significantly increased CCW ($P < 0.001$), CCY ($P < 0.001$), LEA ($P < 0.001$) and SFT ($P = 0.003$).

Neither initial pH (0 h), CWL, WBSF, b*, moisture, total lipids and crude ash content of the *Longissimus lumborum* were not affected ($P > 0.05$) by peNDF8 particle size or R:C ratio (Table 6). However, by increasing the proportion of roughage in the diet, it was observed an increase in L* ($P = 0.036$) of the *Longissimus lumborum* muscle. In addition, the protein content of the *Longissimus lumborum* muscle was greater ($P < 0.001$) for lambs fed larger particle size when for longer peNDF8 size of hay (13 mm).

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Table 5. Performance, carcass traits and physicochemical composition of the *Longissimus lumborum* muscle of lambs fed with two proportions of physically effective neutral detergent fibre (peNDF8) of Tifton-85 hay content and two roughage:concentrate (R:C) ratios

	$_{pe}NDF_8$of hay		R:C ratio			*P* value		
Carcass traits	13 mm	6 mm	700:300	500:500	SEM	peNDF8	R:C	peNDF8 × R:C
Final BW (kg)	31.1	38.1	34.1	39.3	0.51	<0.001	<0.001	0.032
TWG (kg)	7.6	14.6	10.7	15.8	0.44	<0.001	<0.001	0.032
ADG (g/d)	108.2	209.4	152.3	226.1	0.01	<0.001	<0.001	0.033
ADG:DMI (g/g)	0.11	0.18	0.14	0.18	0.012	<0.001	<0.001	0.014
CCW (kg)	14.7	15.1	13.2	16.6	0.27	0.152	<0.001	0.092
CCY (%)	42.1	41.1	40.2	43.0	0.32	0.082	<0.001	0.351
Loin eye area (cm^2)	13.5	13.4	12.3	14.6	0.28	0.763	<0.001	0.751
SFT (mm)	2.38	2.39	2.26	2.51	0.043	0.864	<0.001	0.342
pH meat	5.98	5.78	5.86	6.10	0.048	0.181	0.832	<0.001
a* (redness)	23.0	23.9	23.8	22.8	0.20	0.511	<0.001	0.022
C* (Chroma)	24.4	25.3	25.3	23.9	0.23	0.542	0.645	0.025

SEM, standard error of the mean; ADG, average daily gain; CCW, cold carcass weight; CCY, cold carcass yield; SFT, subcutaneous fat thickness.

Table 6. Physicochemical composition of the *Longissimus lumborum* muscle of lambs fed with two proportions of physically effective neutral detergent fibre ($peNDF_8$) of Tifton-85 hay and two roughage:concentrate (R:C) ratios

	peNDF8 size hay		R:C ratio			*P* value		
Item	13 mm	6 mm	700:300	500:500	SEM	peNDF8	R:C	peNDF8 × R:C
pH 0 h	6.38	6.40	6.37	6.41	0.022	0.543	0.411	0.183
CWL, g/kg	202	179	197	183	0.7	0.110	0.329	0.553
WBSF, N/cm^2	1.87	1.60	1.59	1.88	0.093	0.148	0.117	0.606
Colour parameters								
L*(lightness)	41.7	41.3	42.3	40.7	0.39	0.603	0.033	0.086
b*(yellowness)	8.1	8.0	8.4	7.8	0.20	0.794	0.136	0.097
Moisture, g/kg	746	747	748	745	0.1	0.772	0.291	0.421
Crude protein, g/kg	212	207	210	209	0.1	<0.001	0.802	0.711
Total lipids, g/kg	31.7	34.2	34.4	31.4	0.11	0.262	0.172	0.222
Crude ash, g/kg	9.3	11.2	9.4	11.1	0.07	0.061	0.112	0.381

SEM, standard error of the mean; CWL, cooking weight loss; WBSF, Warner–Bratzler shear force.

There was no interaction or effect of peNDF8 size of hay ($P > 0.05$) on the FA composition of the *Longissimus lumborum* muscle (Table 7). However, increasing the proportion of roughage (R:C ratio of 500:500 to 700:300 g/kg DM) in the diet increased the C12:0, C15:0, C17:0, C18:0 C17:1, and C18:2–*cis*–9–*trans*11, C18:3–*cis*–9–*cis*–12–*cis*–15, C20:5, C22:5, C22:6, ΣSFA, Σ*n*–*3* and TI index. Conversely, decreasing the proportion of roughage to 500 g/kg DM in the diet of lambs increased the concentrations of C14:1, C 16:1–*cis*–9, C18:1–*cis*–9, ΣMUFA, Σ*n*–*6*:Σ*n*–*3* and h/H, as well as enzymatic activity of Δ9desaturase–C16 and Δ9desaturase–C18 in *Longissimus lumborum* muscle.

Discussion

Voluntary DMI is a mechanism that can be affected by associated or isolated factors such as physical (physical satiety by filling the gastrointestinal tract) or physiological (chemical satiety) and the quality of the food (Araújo *et al.*, 2017; Jeon *et al.*, 2019). The concentrate intake tends to influence the total DMI and also its constituents (such as nitrogen compounds), since it is a more palatable and digestible diet component (Realini *et al.*, 2004; Jeon *et al.*, 2019).

The increase in the amount of concentrate in the diet, associated with the reduction in peNDF8 of hay provided greater availability of dietary energy for lambs (NFC), since the reduction in the peNDF8 size of hay (13 to 6 mm) of the hay can have most likely increased passage rate (Van Soest, 1994) allowing for a higher intake of TDN. Although the present study did not measure the concentrations of volatile fatty acids, the literature demonstrates from the many studies that reducing roughage and increasing the concentrate content, the propionate concentration increases from the rumen fermentation, which is more

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Table 7. Fatty acid methyl esters composition (FAME), group, sum or ratio and nutraceutical compounds of the *Longissimus lumborum* muscle of lambs fed diets containing two sizes of physically effective neutral detergent fibre ($peNDF_8$) of Tifton-85 hay and two roughage:concentrate (R:C) ratios

	peNDF8 of hay		R:C ratio			*P* value		
Fatty acids (g/100 g of FAME)	13 mm	6 mm	700:300	500:500	SEM	peNDF8	R:C	peNDF8 × R:C
C12:0	0.06	0.07	0.07	0.06	0.011	0.511	<0.001	0.502
C14:0	1.67	1.61	1.62	1.66	0.042	0.421	0.611	0.061
C14:1	0.06	0.06	0.06	0.07	0.012	0.131	0.031	0.332
C15:0	0.21	0.22	0.25	0.18	0.019	0.672	<0.001	0.230
C16:0	22.5	22.1	22.5	22.1	0.23	0.412	0.442	0.545
C16:1–*cis*9	1.61	1.58	1.53	1.67	0.026	0.554	<0.001	0.283
C17:0	0.81	0.82	0.93	0.71	0.024	0.782	<0.001	0.103
C17:1	0.42	0.41	0.44	0.39	0.014	0.383	0.012	0.312
C18:0	18.2	18.9	19.4	17.7	0.26	0.152	<0.001	0.954
C18:1–*cis*9	36.0	36.0	34.7	37.3	0.33	0.981	<0.001	0.981
C18:2–*cis*9–*cis*12	4.2	4.0	4.1	4.1	0.13	0.663	0.853	0.123
C18:2–*cis*9–*trans* 11	0.33	0.34	0.37	0.29	0.012	0.513	<0.001	0.703
C18:3–*cis*9–*cis*12*cis*15	0.45	0.44	0.55	0.33	0.023	0.665	<0.001	0.207
C20:4	1.53	1.43	1.55	1.41	0.063	0.383	0.243	0.143
C20:5 (EPA)	0.37	0.34	0.43	0.29	0.023	0.365	<0.001	0.161
C22:5 (DPA)	0.53	0.50	0.60	0.44	0.024	0.412	<0.001	0.243
C22:6 (DHA)	0.14	0.13	0.15	0.12	0.015	0.554	<0.001	0.383
Outros ácidos graxos	9.0	9.2	9.1	9.2	0.12	0.361	0.592	0.553
DFA	63.9	64.2	63.9	64.2	0.25	0.612	0.551	0.131
ΣSFA	43.5	43.7	44.7	42.5	0.36	0.820	<0.001	0.571
ΣMUFA	38.1	38.1	36.7	39.5	0.34	0.951	<0.001	0.988
ΣPUFA	7.5	7.2	7.8	7.0	0.23	0.547	0.086	0.134
ΣPUFA:ΣSFA ratio	0.17	0.17	0.17	0.17	0.013	0.602	0.412	0.122
Σ*n–3*	1.49	1.41	1.73	1.18	0.062	0.441	<0.001	0.192
Σ*n–6*	5.7	5.5	5.7	5.5	0.18	0.563	0.612	0.124
Σ*n–6*: Σ*n–3* ratio	4.0	4.0	3.3	4.7	0.11	0.581	<0.001	0.541
h:H ratio	1.80	1.84	1.76	1.88	0.035	0.501	0.053	0.205
Atherogenicity index	0.65	0.64	0.66	0.63	0.015	0.832	0.164	0.256
Thrombogenicity index	1.35	1.38	1.42	1.31	0.023	0.524	0.015	0.426
Enzymatic activity								
Δ9desaturase–C16	6.9	7.0	6.6	7.4	0.13	0.754	<0.001	0.820
Δ9desaturase–C18	66.4	65.5	64.1	67.8	0.5	0.32	<0.001	0.983
Elongase	69.3	69.8	69.3	69.9	0.3	0.26	0.243	0.524

SEM, standard error of the mean; EPA, eicosapentaenoic; DPA, docosapentaenoic; DHA, docosahexaenoic; DFA, desirable fatty acids; h:H ratio, hypocholesterolemic and hypercholesterolemic fatty acid index calculated as [(ΣC18:1 *cis–9*, C18:2 *n–6*, C20:4 *n–6*, C18:3 *n–3*, C20:3 *n–6*, C20:5 *n–3* and C22:6 *n–3*)/(ΣC14:0 and C16:0)]; atherogenicity index = [(C12 + 4 × C14 + C16)/(ΣMUFA + Σ*n–6* + Σ*n–3*)]; thrombogenicity index = (C14 + C16 + C18)/[0.5 × ΣMUFA + 0.5 × Σ*n–6* + 3 × /(Σ*n–6*)].

energy-efficient than acetate, as it does not produce methane and reduces hydrogen in the environment ruminal (Medeiros *et al.*, 2015; Morais *et al.*, 2015; Jeon *et al.*, 2019). In addition, propionate has the gluconeogenic potential from oxidation by citric acid, which makes propionate more flexible as an energy source than acetate, increasing the energy density of the diet (Owens, 1980).

The CCW is influenced by the proportions of bone, muscle and adipose tissues, which are indicators of growth (Silva *et al.*, 2016). In addition to being influenced by BW, the animals that obtained the highest BW were those that obtained the highest HCW. The CCY of lambs fed with a higher roughage proportion (700 g/kg DM) was lower, because this variable is dependent on the contents of the digestive system, which may represent

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8–18% of BW (Villarroel *et al*., 2006). Thus, when the proportion of roughage in the diet is higher, the gastrointestinal tract becomes more developed in length due to an increase in residence time of the digesta needed to maximize fermentation (Van Soest, 1994).

LEA and SFT also increased once roughage proportion was decreased. The LEA is an indication of the animal's muscularity, representing the amount of meat that can be commercialized. An increase in LEA can be related to a greater availability of energy in the diets with higher proportions of concentrate (Lima *et al*., 2018), which is expected to enhance animal performance. Indeed, our data have shown that animals fed higher proportions of concentrate were heavier at the end of the trial, had a greater TWG, a greater ADG and were more efficient in converting feed consumed into kg of BW (Table 3). The roughage reduction to 500 g/kg DM also has increased the SFT, which is an indicator of energy surplus caused by an increase in levels of propionic acid in the rumen, which in turn leads to an increase in the circulating glucose stimulating insulin release and lipogenesis thereafter (Jenkins, 1993).

The final pH (24 h) of sheep meat varies between 5.5 and 5.9, values above 6.0 can be found in cases of depletion of muscle glycogen stores before slaughter (Ramos and Gomide, 2007). Animals that received diets with different particle sizes had different carcass pH 24 h. For larger particle sizes (13 mm), there was a decrease in pH 24 h from increasing the proportion of concentrate in the diets, whereas when lambs were fed smaller particle sizes (6 mm), the pH 24 h increased as we increased concentrate in their diets going above the 6.0 threshold. These results corroborate with our findings regarding greater LEA in the carcass of animals fed higher concentrate diets (Table 4). In this case, a greater muscularity would promote higher muscle turnover and higher demand for glucose with the expense of depleted glycogen (Ramos and Gomide, 2007). According to Bonacina *et al*. (2011), the final pH of the meat could negatively influence the quality of it; however, it is worth noting that despite the differences found in pH 24 h in the present study, no noticeable changes were found in the physicochemical composition of the meat.

The colour of the muscle is determined by the amount of myoglobin and the relative proportions of clearance, which can be found in myoglobin-deduced (purple), oximioglobin (reddish) and metamioglobin (brown colour). Lambs with greater slaughter weight and greater amount of fat may present a meat with a greater intensity of a* and C* index colour. The L* parameter of the *Longissimus lumborum* decreased with the increase in the proportion of concentrate in the diet (500 g/kg DM). In the present study, it was observed that the meat (i.e. *Longissimus lumborum*) of lambs fed higher concentrate proportion in their diet are redder if they are fed larger particle sizes. Though, the proportion of roughage (or concentrate) was not a determinant of the redness of the meat.

The interaction between R:C and particle size did not affect the lipid profile of the lamb meat; however, the variation of R:C ratio of the diet caused the FA profile of the meat to change. The higher roughage proportion (700 g/kg DM) in the diet promoted an increase in FA in most of the ΣSFA and ΣPUFA, also increasing the total SFA.

The C18:0 was more ubiquitously present as SFA moieties in the meat, probably due to the higher dietary content of C18:0. Lambs fed higher concentrate proportions in the diet present higher C18:0 content in the meat. Nevertheless, C18:0 is characterized as a neutral factor in the appearance of cardiovascular diseases, unlike other FA (C18:1), which acts on the reduction of serum cholesterol (French *et al*., 2000).

The C14:1, C16:1 and C18:1 were observed in greater concentrations in *Longissimus lumborum* of the lambs fed with higher concentrate proportion (500 g/kg DM of roughage). Most likely, this is due to an increase in the amount of NFC (e.g. starch) present in the higher concentrate diets (Table 2) which provides an increase of glucose flow and plasma insulin thereafter, lipogenesis and Δ9–desaturase enzyme activity, which in turn could have triggered the ruminal dissociation of dietary lipids, allowing for the contribution of C18:1–*trans*–11, an intermediate in the process of biohydrogenation in the rumen. Consequently, we would have had an increased absorption in the small intestine, stimulating the production of rumenic acid (C18:2–cis9–trans 11) in the animal tissues, from the action of Δ9–desaturase (Sinclair, 2007; Wood *et al*., 2008).

The conjugated linoleic acid (CLA) was also found in a higher proportion in the meat of lambs fed high roughage diet due to the higher dietary supply of linoleic acid (C18:2). A high intake of PUFA causes an inhibition in the bacteria that perform the biohydrogenation, therefore accumulating the intermediates of this process that will reach the small intestine and be absorbed to be incorporated into the muscle (Jenkins, 1993). Previous research has shown that increasing roughage proportion in the diet of animals increases CLA concentration in the milk and meat (Lawless *et al*., 1998).

Lambs fed a higher amount of roughage (700 g/kg DM) presented a higher concentration of linolenic (C18:3), but also this diet had greater content of C18:3. When a large intake of unsaturated FA occurs, the capacity of the microorganisms of the rumen to biohydrogenate can be impaired, resulting in fat to pass the rumen unbroken and consequently increase the intestinal absorption of unsaturated FA. If more unsaturated FA are absorbed, an increased deposition of PUFA in the muscle will be absorbed, which in turn will improve the nutritional and functional quality of the meat (Geay *et al*., 2001). In addition, linolenic acid (C18:2) is a precursor of eicosapentaenoic Σ*n–3* (C20:5, EPA), docosapentaenoic acid (C22:5, DPA) and docosahexaenoic acid (C22:6, DHA), thus feeding higher roughage proportion in the diets, the concentration of these FA in the meat of the lambs would also increase, corroborating with what was observed in the present study.

The EPA, DPA and DHA FA are considered essential because they are not synthesized by the body, therefore necessary in the human diet for the proper functioning of the brain, and its presence in cell membranes (Parodi, 2016). *Longiussimus lumborum* muscle of lambs fed a higher proportion of concentrate had a higher concentration of Σ*n–6*:Σ*n–3* in the PUFA ratio than animals fed with higher roughage proportion (4.72 *v*. 3.29, respectively). Often time, an increase in the Σ*n–6* concentration is recommended to maintain a dietary balance between the two types of FA (DHE, 1994), since they work together, promoting health and organic balance. More importantly, even both diets presented a desirable ratio Σ*n–6*:Σ*n–3*, a smaller ratio is preferred in order to decrease risks of many chronic diet-related diseases observed in Western societies (Simopoulos, 2002). Since these FA work together, while the metabolic products of Σ*n–6* promote inflammation, cardiovascular disease, cancer and autoimmune diseases, Σ*n–3* exert suppressive effects (Oliveira *et al*., 2013).

Conclusion

Non-castrated, 4-month-old male lambs have been evaluated on their performance and carcass traits upon being fed diets with

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varying particle sizes and different proportions of R:C ratio in an attempt to change carcass FA composition and produce a healthier meat product. Lambs fed diets with higher roughage proportion (700 g/kg DM) had lower FBW, lower weight gains, decreased performance with smaller ADG and were less efficient. Decreasing particle (13 to 6 mm) of this diet have improved all these metrics whereas for diets with lower roughage proportions (500 g/kg DM), a decrease in particle size did not affect performance nor carcass traits. Decreasing the proportion of roughage in the diet promoted greater CCW and yield, increased muscularity and increased the subcutaneous fat in the carcass. Regarding physicochemical meat characteristics, the higher proportion of roughage in the diet promoted an increase in final carcass pH and final carcass crude protein whereas a simultaneous decrease in roughage proportion and particle size have further decreased meat redness and colour saturation with no effects on toughness, cooking losses and total lipid content. However, decreasing roughage proportion in the diet reduced the deposition of SFA and thrombogenicity index in the meat while increasing the $\Sigma n{-}6{:}\Sigma n{-}3$ and h:H ratios promoting a healthier and higher quality product.

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Conflict of interest. None.

Ethical standards. This study was carried out in accordance with the recommendations of the Brazil's National Council for the Control of Animal Experimentation and all experimental procedures were approved by the Ethics of Animal Experiments Committee of the Federal University of Bahia (protocol # 37/2014).

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