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Tropical agroforestry providing physically effective fiber reduces concentrate use without impairing goat performance

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Abstract This study evaluated the effects of supplements containing varying levels of physically effective fiber (peNDF) on the performance, carcass traits, tissue composition of commercial cuts, and physicochemical characteristics of meat from goats finished on tropical agroforestry enriched with *Cenchrus ciliaris*. Twenty-four F1 crossbred goats (Boer × Creole) with average initial weight: 19.5 ± 1.6 kg were assigned to a completely randomized design with four peNDF levels (19.9%, 23.2%, 26.7%, and 30% of dry matter) and six replicates. The supplement consisted of soybean meal, corn meal, wheat bran, mineral premix, and *Sida cordifolia* hay. Increasing peNDF levels led to a linear reduction ($p < 0.05$) in total dry matter intake (DMI), and body weight, without affecting supplement DMI. Conversely, neutral and acid detergent fiber intake increased linearly ($p < 0.05$) with higher peNDF levels. Crude protein intake and DM digestibility remained unaffected. Total gain and average daily gain declined linearly with increasing peNDF, although final body weight and feed efficiency were not influenced. Carcass weight variables showed no significant differences; however, hot and cold carcass yields decreased linearly ($p < 0.01$) as peNDF increased. Only rumen yield was affected among visceral organs, increasing linearly ($p = 0.012$). Of the commercial cuts, only the loin showed reduced weight with higher peNDF ($p = 0.018$). Shoulder and leg yields (%carcass) increased linearly, while fat deposition in the shoulder, ribs, and loin declined. In conclusion, the optimal use of physically effective fiber (peNDF) from tropical forages enhances the utilization of Caatinga resources and can reduce the need for concentrated feeds. Moderate inclusion levels (≤ 23%) may support rumen development and maintain animal performance, whereas higher levels might impair finishing efficiency due to reduced energy availability and fat deposition.

Keywords *Cenchrus ciliaris* · Caatinga biome · Fiber · Grazing · Performance

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Introduction

The Caatinga biome, an exclusive semi-arid ecosystem of northeastern Brazil, holds significant

potential for integration into agroforestry systems. Incorporating native Caatinga vegetation alongside cultivated species can enhance biodiversity, improve soil quality, and increase resilience to climate variability (Pereira Filho et al. 2013). Traditional knowledge in goat and sheep husbandry, adapted to the region's conditions, plays a crucial role in sustaining these systems (Silva et al. 2015). Through strategic grazing management, rotational use of pastures, and preservation of native forage plants, small ruminant production can coexist with environmental conservation, and to reducing the use of concentrated foods that increase production costs and make it difficult for rural producers to remain in the activity (Formiga et al. 2011; Lima Junior et al. 2025). This integrated approach supports rural livelihoods while ensuring the long-term preservation of the Caatinga's ecological integrity.

In arid and semiarid regions, ruminants primarily rely on native pastures and crop residues to meet their nutritional requirements. However, these feed resources typically exhibit low dietary quality, characterized by reduced crude protein content and high levels of indigestible fiber (Tikam et al. 2014; Bandeira et al. 2017). Feed limitation becomes more pronounced during the dry season, when high-quality forages become scarce or economically unfeasible, particularly for smallholder farmers (Salem and Smith 2008). A technically sound strategy to mitigate forage shortages is the conservation of surplus biomass produced during the rainy season, such as hay, to ensure adequate feeding during the dry period (Balehegn et al. 2022).

In the Brazilian semiarid region, goat production systems are predominantly extensive and strongly dependent on native Caatinga biome vegetation, which consists of trees, shrubs, cacti, bromeliads, and herbaceous annuals (Bandeira et al. 2017). Although dry matter production is high during the rainy season, much of the available forage is located in tree canopies, beyond the reach of grazing animals. During the dry season, the availability of senescent herbaceous plants and litter increases, but these materials are nutritionally inadequate to meet maintenance requirements (Silva et al. 2015). Moreover, the carrying capacity of the Caatinga biome is limited, making it essential to adopt management practices that promote herbaceous regrowth and increase forage availability (Pereira Filho et al. 2013).

As a result of these constraints, animals in this region are typically slaughtered at over 12 months of age, exhibiting low average daily gain and final body weights ranging from 30 to 35 kg. This production profile fails to meet the demands of the modern consumer market, which increasingly favors early maturing animals with carcass weights between 8 and 12 kg (Soares et al. 2016). Therefore, supplementation strategies under grazing conditions are crucial to enhance nutrient intake and improve animal performance.

According to Santos et al. (2008), the selectivity index of goats and sheep in areas of the Caatinga Biome is high, characterized by a higher proportion of Malvaceae and Poaceae species. This index varies throughout the year and is directly related to the ingestive behavior of sheep. Therefore, it is essential to know how to select the supplement, especially regarding fiber content, to avoid substitution effects and meet the animals' requirements.

The exclusive use of commercial concentrate feeds is often cost-prohibitive, especially for small-scale producers. At the same time, forage conservation practices are underutilized, resulting in the loss of valuable biomass produced during the rainy season (Bandeira et al. 2017). In this context, the rational use of native herbaceous forages, particularly through haymaking, emerges as a promising alternative for supplementing small ruminants during feed scarcity (Pereira Filho et al. 2013).

Among the native species with forage potential, *Sida cordifolia* (malva-branca) stands out due to its vigorous growth during the rainy season. Nevertheless, its high neutral detergent fiber (NDF) content, even in fresh form, is directly associated with low voluntary intake. To overcome this limitation, including *Sida cordifolia* hay in combination with concentrate supplements may enhance its utilization, even though its fiber has reduced physical effectiveness (Pereira Filho et al. 2013; Oliveira et al. 2025).

The concept of physically effective fiber (peNDF) refers to the portion of dietary NDF that combines chemical fiber content with particle size sufficient to stimulate chewing activity, promote saliva secretion, and stabilize ruminal pH (Van Soest et al. 1991; Lammers et al. 1996; Kononoff et al. 2003). Adequate peNDF intake is essential for maintaining rumen health, enhancing fiber degradation, and supporting efficient nutrient use. In grazing systems of the Caatinga biome, where forage availability fluctuates and

goats often rely on concentrate supplements, the strategic use of agroforestry forages rich in peNDF may reduce concentrate requirements while sustaining performance. Based on this framework, we hypothesized that: (1) increasing levels of peNDF supplied through native agroforestry forages would improve rumen function and nutrient utilization; (2) goats receiving optimal peNDF supplementation would maintain growth performance and carcass traits despite reduced concentrate intake.

Therefore, the objective of this study was to evaluate the levels of peNDF to reduce the use of the concentrate feed in goat diets as its effect on the performance, carcass traits, tissue composition of commercial cuts, and physicochemical characteristics of meat from goats fattening on tropical agroforestry enriched with *Cenchrus ciliaris*.

Material and methods

Ethical considerations, location, animals and experimental design

All experimental procedures complied with the Ethical Principles of Animal Experimentation established by the Animal Ethics Committee of the Federal University of Campina Grande (FUCG), Paraíba, Brazil, under protocol number 264/2015.

The study was conducted at the Experimental Station of the Federal University of Campina Grande (07°05′ 10″ N; 37°15′ 43″ W), located in Paraíba, Brazil, between September and December. The region has a BShw climate, according to the Köppen classification: tropical semi-arid, with a short rainy season concentrated in March and April, and total annual precipitation averaging 700 mm. During the study, average temperatures were 28 °C with 60% relative humidity, and rainfall totaled 62 mm, distributed as 11, 17, and 44 mm in September, October, and November, respectively.

Animals and experimental design

Twenty-four non-castrated crossbred F1 crossbred goats (Boer × Creole), with an average initial body weight of 19.5 ± 1.6 kg and approximately five months of age, were individually identified with numbered collars. A completely randomized design was used, with four treatments consisting of supplements formulated with increasing levels of peNDF: 19.9%, 23.2%, 26.7%, and 30% on a dry matter (DM) basis. Each treatment included six replicates (goats). The experimental period lasted 100 days, including 15 days for adaptation and 85 days for data collection.

Grazing and supplementation management

The experimental pasture area consisted of 2.4 ha, divided into four paddocks of 0.6 ha each, equipped with shelter and water troughs. Selective thinning of undesirable woody species was performed to reduce canopy cover to 15% (Pereira Filho et al. 2013), followed by broadcasting of Buffel grass seeds (*Cenchrus ciliaris* L. cv. Biloela). The available dry matter in the pasture was composed of Buffel grass, herbaceous dicotyledons, and litter. Samples of each component were collected monthly (September to December) for chemical composition analysis (Table 1).

Three rumen-cannulated, castrated Boer-cross goats (average body weight: 20 kg) were used exclusively to characterize the botanical and chemical composition of the selected forage through ruminal extrusa sampling. These animals did not receive the experimental treatments and were maintained under continuous grazing conditions without supplementation, with ad libitum access to water and a mineral mix, ensuring that extrusa samples accurately reflected forage selection under natural grazing.

The fistulated animals were subjected to the same feeding management as the experimental animals and were kept in an area similar to and contiguous with the experimental area. During the night, the fistulated animals were subjected to the same procedures as the experimental animals, kept in pens with individual waterers and feeders.

Rumen extrusa samples were collected on alternate days, totaling four collections per experimental period: two conducted in the morning (08:00 h) and two in the afternoon (14:00 h), following protocols adapted from Santos et al. (2008). Prior to morning sampling, animals were subjected to a 15-h fasting period, after which the entire rumen contents were removed, temporarily stored, and reintroduced immediately after the collection procedure. Following rumen evacuation, animals were allowed to graze for 1 h, after which the ingested material (extrusa)

Table 1 Chemical composition (%DM) of herbaceous vegetation and litter/stubble from september to december

Item	Buffel grass				Dicotyledonous				Litter/stubble			
	Sep	Oct	Nov	Dec	Sep	Oct	Nov	Dec	Sep	Oct	Nov	Dec
DM	73.85	70.14	70.94	74.06	71.58	68.77	70.38	67.21	85.95	85.69	86.89	86.69
CP	3.06	3.22	3.05	2.99	3.55	4.48	3.53	3.42	4.67	4.35	3.88	3.03
NDF	86.98	85.46	89.44	88.28	87.09	86.49	86.44	89.06	86.02	87.71	87.05	90.92
aNDF	80.16	79.32	78.12	81.41	81.68	79.22	79.24	83.13	78.59	80.38	80.64	83.78
NDIN	85.19	84.02	88.15	86.63	84.56	83.94	84.52	86.49	82.83	85.24	85.17	89.13
ADF	58.13	59.85	65.47	61.40	69.54	75.06	71.12	73.57	70.99	69.03	71.00	71.92
ADIN	56.99	58.89	64.45	60.46	66.81	71.96	68.94	71.55	67.96	66.67	68.69	70.22
HEM	28.85	25.60	23.96	26.88	17.54	11.43	15.32	15.48	15.03	18.67	16.05	19.00
Ash	8.92	8.27	8.05	8.09	5.00	5.09	4.69	3.82	9.72	8.36	6.32	5.19

DM Dry matter, NDF Neutral detergent fiber, aNDF Neutral detergent fiber corrected for ash and protein, NDIN Neutral detergent insoluble nitrogen, ADF Acid detergent fiber, ADIN Acid detergent insoluble nitrogen, CP Crude protein, HEM Hemicellulose; Sep = September, Oct = October, Nov = November, Dec = December

was retrieved via the rumen cannula, homogenized, and preserved for subsequent chemical analyses. The same procedures were applied for afternoon collections, without fasting, to account for diurnal variation in forage selection.

This approach allowed for an accurate and representative estimation of the diet selected by grazing animals under the experimental conditions. To minimize the effect of paddock-specific pasture composition, goats were rotated across all paddocks every two days throughout the study. The initial stocking rate was 0.44 AU/ha, equivalent to 24 goats averaging 20 kg across 2.4 ha (200 kg/ha live weight). Grazing occurred from 8:00 to 17:00, after which goats were moved to individual pens (equipped with feed and water) for supplementation, simulating the breeding systems commonly used for grazing with supplementation.

Diets consisted of selected forage and a concentrate supplement formulated with soybean meal, ground corn, and wheat bran. The supplement was designed to meet the nutritional requirements of 20-kg goats with an average daily gain of 150 g, according to NRC (2007), and was offered at 1.5% of body weight, with weekly adjustments. The treatment with the lowest inclusion of 19.9% peNDF did not contain mallow hay in the supplement, therefore the forage(F)-to-concentrate(C) ratio of the supplement was 0:100; other treatments the ratio R:C was 10:90; 20:80 and 30:70 in treatments 23.3; 26.7; and 30% of peNDF inclusion, respectively.

To ensure varying peNDF levels, *Sida cordifolia* (malva-branca), an herbaceous dicotyledon abundant in the area and harvested during flowering (1.0–1.5 m height), was processed into hay, ground, and incorporated into the supplement. Particle size was determined using the Penn State Particle Separator (effectiveness factor: 0.75), as described by Lammers et al. (1996) and modified by Kononoff et al. (2003). The physically effective fiber (peNDF) content was calculated and used to define treatment levels.

Feed Intake and digestibility

Feed intake and apparent dry matter digestibility were estimated using fecal output in combination with in vitro digestibility of ruminally collected extrusa. Fecal output was determined using the external marker LIPE® (purified lignin isolated from *Eucalyptus* spp.), following the methodology described by Saliba (2005). LIPE® was administered at a dose of 250 mg animal^{-1} day^{-1} via an esophageal probe for six consecutive days to allow marker stabilization in the digestive tract.

For fecal production, all 24 animals were used; that is, the external marker was introduced via probe in all animals. The fistulated animals were used for digestibility. In this way, intake was estimated by associating the fecal production of the 24 animals with the results obtained from the digestibility of the three fistulated animals.

Fecal samples were collected directly from the rectum on days 4, 5, and 6 of marker administration, immediately refrigerated, pre-dried in a forced-air oven at 65 °C for 72 h, ground to pass a 1-mm screen, and analyzed by infrared spectrophotometry (Perkin-Elmer®, Germany) for LIPE® concentration. Fecal output was calculated as the ratio between the daily dose of LIPE® administered and its concentration in feces.

The chemical composition of the consumed diet was estimated using ruminal extrusa collected from three rumen-fistulated goats managed under the same grazing and supplementation conditions as the experimental animals. After a 12-h fasting period, the rumen contents were completely evacuated, and the animals were allowed to graze for 40 min. The ingested material (extrusa) was collected, homogenized, and sampled for chemical analysis. In addition, representative samples of the supplement ingredients (soybean meal, corn meal, wheat bran, and *Sida cordifolia* hay) were analyzed.

Dry matter digestibility was estimated based on the indigestible neutral detergent fiber (iNDF) fraction, determined from ruminal extrusa and incubated feed ingredients, following standardized in situ or in vitro incubation procedures. Digestibility coefficients were calculated using the ratio between fecal output and estimated dry matter intake derived from marker data and diet composition.

Chemical composition analyses

Samples of feed, extrusa (Table 2), diets (Table 3), and feces were pre-dried (55 °C, 72 h), ground (1.0 mm sieve), and stored. Analyses followed AOAC (2015): dry matter (967.03), ash (942.05), crude protein (981.10), and ether extract (920.29). NDF and ADF were analyzed per Van Soest et al. (1991) using nonwoven bags (Senger et al. 2008) and amylase inclusion (Sigma A3306). aNDFom was calculated excluding residual ash, corrected for protein. The NDF residue was incinerated at 600ºC for 4 h; the protein correction was determined by subtraction between the neutral detergent insoluble protein (NDIP). The content of NDIP and acid detergent insoluble proteins (ADIP) were obtained following the methodologies proposed by Licitra et al. (1996). Acid detergent lignin (ADL) was determined by methodology described in AOAC (2015) method 973.18, where the ADF residue was treated with 72% sulfuric acid. Hemicellulose was determined by subtracting the ADF (sum of cellulose and lignin) from NDF (sum of cellulose, hemicellulose, and lignin).

Performance, carcass traits, commercial cuts and tissue composition

Body weights (BW) were recorded at the start, every 21 days, and pre-slaughter. Methods for animal and carcass evaluation followed Cezar and Sousa (2007). After 24 h of solid feed deprivation and 16 h on a liquid diet, animals were weighed for slaughter weight (SW). Slaughter occurred at UFCG's Meat Evaluation Unit. Carcasses were identified, hot carcass weight (HCW) was recorded, chilled at 4 °C for 24 h, and cold carcass weight (CCW) was measured. $\text{Chilling loss}\,(\%) = [(\text{HCW} - \text{CCW})/\text{HCW}] \times 100$. Hot and cold carcass yields were: $\text{HCY} = (\text{HCW}/\text{SW}) \times 100$ and $\text{CCY} = (\text{CCW}/\text{SW}) \times 100$.

$\text{Viscera yield} = (\text{viscera weight}/\text{SW}) \times 100$. Gastrointestinal tract (GIT) weights were recorded full and empty. Bladders and gall bladders

Table 2 Chemical composition of the extrusa and supplement ingredients (g/kg DM)

Ingredients[a]	Dry matter	Ash	Crude protein	NDF	NDIN	ADF	ADIN
Rumen extrusa[b]	176.12	71.68	112.18	662.65	53.46	503.73	44.21
Soybean Meal	819.53	72.47	441.56	198.47	67.84	170.35	36.74
Corn Meal	823.82	34.97	104.54	170.86	41.76	78.24	17.93
Wheat Bran	819.55	52.36	166.27	468.95	47.07	151.22	21.34
Mallow Hay	827.84	73.85	95.26	724.94	58.25	629.13	43.85

DM Dry matter, CP Crude protein, NDF Neutral detergent fiber, aNDF Neutral detergent fiber corrected for ash and protein, NDIN Neutral detergent insoluble nitrogen, ADF Acid detergent fiber, ADIN Acid detergent insoluble nitrogen

[b]pasture selected by fistulated animals

Table 3 Proportions of experimental ingredients and chemical composition of supplements with different proportions of physically effective fiber (peNDF)

Item	Physically effective fiber (peNDF, %DM)			
	19.9	23.3	26.7	30.0
Ingredients (g/kg DM)				
Soybean meal	142.70	128.40	114.20	99.90
Ground corn	500.00	450.00	400.00	350.00
Wheat bran	324.00	291.60	259.20	226.80
White mallow hay	0.00	100.0	200.00	300.00
Limestone	13.30	12.0	10.60	9.30
Mineral mixture[a]	20.00	18.00	16.00	14.00
Chemical composition (g/kg DM)				
Dry matter (g/kg as fed)	794.43	795.04	795.62	79.62
Crude protein	169.12	161.32	153.53	145.63
$_{a}$NDFom[b]	265.64	310.61	355.62	400.54
Neutral detergent insoluble nitrogen	45.86	46.93	48.02	49.03
Acid detergente fiber	112.46	163.72	215.01	266.33
Aciddetergent insoluble nitrogen	21.15	23.34	25.53	27.74
Hemicelulosis	153.24	146.93	140.54	134.25
Physically effective fiber (peNDF)[c]	199.22	233.04	266.73	300.42

[a]Nutrients/kg of product: 150 g of calcium; 87 g of phosphorus; 5,050 mg of magnesium; 1500 mg of iron; 100 mg of cobalt; 400 mg of copper; 1000 mg of manganese; 2000 mg zinc; 61 mg of iodine; 11.7 mg of selenium; 13.8 g of sulfur; 148 g of sodium; maximum 750 mg of fluoride

[b]$_{a}$NDF assayed with a heat stable amylase and expressed exclusive of residual ash; [c]Diet particle size distribution was measured using the Penn State Particle Separator (Kononoff et al. 2003); Physical effectiveness factor determined as the proportion of particles retained on 2 sieves (8 and 19 mm) (Lammers et al. 1996) and on 3 sieves (1.8, 8 and 19 mm) (Kononoff et al. 2003), respectively

were emptied and washed. Empty body weight (EBW) = SW − [(GIT − empty GIT) + urine + bile] . Biological yield = (EBW/SW) × 100.

After chilling, carcasses were split longitudinally. The left half was divided into five commercial cuts: neck, shoulder, ribs, loin, and leg (Cezar and Sousa 2007). Cuts were weighed to assess regional carcass composition. Cuts were frozen at −20 °C, later thawed, weighed (precision: 0.5 g), and dissected into subcutaneous fat, intermuscular fat, muscle, and bone. Total fat was calculated by summing both fat types. Results were expressed as absolute weights and yield (g/kg) relative to reconstituted cut weight.

Statistical analysis

The data were analyzed in a completely randomized design, with four treatments [increasing levels of physically effective fiber (peNDF): 19.9%, 23.2%, 26.7% and 30% on a dry matter (DM) basis] and six replicates, represented by the F1 crossbred goats (Boer × Creole), i.e., each goat corresponding to one replicate. In this case, we have six replicates per treatment. Initial weight was used as a covariate, and the statistical model used was:

$$Yij = \mu + \tau i + \beta(Xij - X) + \in ij$$

onde: Yij = is the observed value of the response variable for the j-th replicate of the i-th treatment; μ = is the overall mean of the experiment; τi: Is the effect of the i-th treatment (I = 1,…,4) β: is the linear regression coefficient that indicates the relationship between the response variable (Y) and the covariate (X); Xij = is the observed value of the covariate (initial live weight) in plot ij; X: is the overall mean of the covariate throughout the experiment ϵij: is the random experimental error.

The data were subjected to analysis of covariance (ANOVA). The effect of peNDF levels was evaluated using polynomial contrast (linear and quadratic), as well as subjecting the means to Tukey's

test. The PROC GLM procedure in SAS statistical software (version 6; SAS Institute, Cary, NC, 2004) was used for all analyses, with a significance level of 5%.

Results

Dry matter intake (DMI, pasture and total) varied among all treatments ($p < 0.05$), comparing goats receiving 19.9% and 30.0% of peNDF, it was observed DMI of 533 and 419 g/day respectively, and when expressed in BW metabolic g/kg$^{0.75}$ the values were 55.61 and 39.59 g/kg (Table 4). The values for aNDFom intake (g/d) and ADF (g/d), as expected, were inversely proportional to those observed for dry matter, with the highest intake (165.14 and 104.13) for animals supplemented with peNDF and the lowest (113 and 44.56) for animals supplemented with 19% peNDF, with animals in the other treatments showing intermediate values.

Increasing the level of physically effective fiber (peNDF) in the supplement resulted in a linear decrease ($p = 0.001$) in pasture DMI by orthogonal contrast, as well as in total dry matter intake (DMI) expressed in g/day, % body weight (BW), and g/kg$^{0.75}$. However, no significant effect was observed on the DM intake of the supplement itself ($p = 0.393$). Conversely, total intake of NDF ($p = 0.011$) and ADF ($p = 0.001$) increased linearly as the peNDF level in the supplement increased. Crude protein intake and DM digestibility were not influenced ($p > 0.05$) by the peNDF content of the supplement.

Comparing the average weight gains of the animals (Table 5), it was observed that goats supplemented with 19.9% and 23.3% of peNDF inclusion in goat diet showed similar total gains and ADG (6.07 kg and 86.67 g/d; 6.10 kg and 87.14 g/d, respectively), but total gains and ADG were higher ($p < 0.05$) than those obtained by animals that received 30% NDF (5.00 kg and 71.43 g/d, respectively), with animals supplemented with 26.7% showing intermediate gains and similar ($p > 0.05$) to the other treatments. The effects of peNDF level did not alter carcass weights, but are reflected in the higher hot (43.79%) and cold (43.11%) carcass yield observed for the 19.9% pe NDF treatment ($p < 0.05$) compared to the other treatments, which were similar to each other ($p > 0.05$).

From the polynomial contrast, total weight gain (TWG) and average daily gain (ADG) showed a linear reduction ($p < 0.011$) with increasing levels of peNDF in the supplement. However, final body weight and feed conversion efficiency were not significantly affected ($p > 0.05$) by the peNDF levels. Likewise, slaughter weight, empty body weight, hot carcass weight, and cold carcass weight were not influenced ($p > 0.05$) by the different levels of peNDF in the supplement. Nevertheless, both hot ($p = 0.005$)

Table 4 Nutrient intake and dry matter digestibility in goats supplemented with different proportions of physically effective fiber (peNDF)

Item	Physically effective fiber (peNDF, %DM)				SEM[a]	*p*-value	
	19.9	23.3	26.7	30.0		Linear	Quadratic
DMI pasture (g/d)	251.0a	184.0b	130.0c	67.00d	23.50	0.001	0.933
DMI suplem (g/d)	382.00	386.00	364.00	353.00	29.50	0.393	0,798
DMI total (g)	633.00a	570.00b	494.00c	419.00d	38.10	0.001	0.883
DMI (%BW)	2.81a	2.65b	2.35c	2.02d	0.17	0.001	0.634
DMI (g/kg$^{0.75}$)	55.61a	50.20b	45.32c	39.50d	1.95	0.001	0.919
Crude protein (g/d)	70.84	67.50	62.15	58.34	3.03	0.117	0.968
$_{a}$NDFom[c] (g/d)	113,00c	132.23ab	147.45ab	165.14a	8.42	0.011	0.933
Acid detergent fiber (g/d)	44.56c	65.90bc	84.51ab	104.13a	7.49	0.001	0.913
Digestibility DM (g/100 g ingested)	57.91	57.30	57.83	57.80	1.56	0.997	0.937

[a]SEM = Standard error of the mean; [b]Significant when $p < 0.05$ from polynomial contrast (linear and quadratic); [c]$_{a}$NDF assayed with a heat stable amylase and expressed exclusive of residual ash

Means followed by different lowercase letters differ significantly in treatments according to Tukey's test at a 5% significance level

Table 5 Performance and carcass traits of goats supplemented with different proportions of physically effective fiber (peNDF)

Variables	Physically effective fiber (peNDF, %DM)				SEM[a]	*p*-value[b]	
	19.9	23.3	26.7	30.0		Linear	Quadratic
Performance							
Initial BW (kg)	19.60	19.71	19.48	19.40	0.83	0.908	0.943
Final BW (kg)	25.66	25.87	24.48	23.47	0.94	0.354	0.755
Total weight gain (kg)	6.07a	6.10a	5.00ab	4.07b	0.32	0.011	0.404
Average daily gain (g/d)	86.67a	87.14a	71.43ab	58.10b	4.61	0.011	0.406
Feed efficiency (g/g)[c]	0.14	0.16	0.15	0.14	0.02	0.951	0.974
Carcass traits							
Slaughter BW (kg)	23.97	24.06	22.87	22.00	0.88	0.383	0.795
Empty BW (kg)	18.89	17.82	16.95	16.27	0.75	0.199	0.896
Hot carcass weight (kg)	10.58	9.80	9.09	8.80	0.46	0.145	0.791
Cold carcass weight (kg)	10.35	9.39	8.92	8.55	0.44	0.140	0.742
Biological carcass yield (%)	55.64	54.87	53.62	53.49	0.42	0.056	0.587
Hot carcass yield (%)	43.79a	40.51b	39.67b	39.40b	0.59	0.005	0.143
Cold carcass yield (%)	43.11a	38.84b	38.94b	38.33b	0.58	0.003	0.060

[a]SEM = Standard error of the mean; [b]Significant when $p < 0.05$ from polynomial contrast (linear and quadratic); [c]Average daily gain-ADG: Dry matter intake-DMI ratio

Means followed by different lowercase letters differ significantly in treatments according to Tukey's test at a 5% significance level

and cold ($p = 0.003$) carcass yields declined linearly as the peNDF level increased.

When evaluating the effect of NDF levels on the weight and yield of organs and viscera (Table 6), it was observed by the mean test that only the rumen yield was altered, with the lowest yield (5.32%) occurring in the treatment with the inclusion of 19.9% peNDF and being different ($p < 0.05$) from that obtained in the other levels of inclusion of peNDF. The weights of the rumen, reticulum, omasum, abomasum, intestines, liver, heart, kidneys, and visceral fat were not altered ($p > 0.05$) by the increased peNDF level in the supplement from the polynomial contrast. Among the yield parameters of these organs, only the rumen yield was affected, showing a linear increase ($p = 0.012$) with higher peNDF levels.

Among the five cuts evaluated and described in Table 7, based on the mean test, only the inclusion of peNDF affected loin weight and shoulder yield ($p < 0.05$); with the highest loin weights occurring in the treatments with 19.9% of peNDF (0.581 kg) and 23.3% NDF (0.532 kg), which were similar to each other but different from the weight observed in the other treatments; regarding shoulder yield, the 21.12% obtained in the treatment with 30% of peNDF inclusion was higher than the 19.41%, 19.47%, and 19.70% obtained for the treatments with 19.9%, 23.3%, and 26.7% NDF, respectively. From the polynomial contrast, only the loin exhibited a significant change, with a linear reduction in weight ($p = 0.018$) as the peNDF level increased. Regarding the yields of commercial cuts relative to cold carcass weight, linear increases were observed for shoulder ($p = 0.005$) and leg yields ($p = 0.009$).

Based on the mean comparison test, in none of the cuts was the weight of the muscles and bones influenced by the treatments ($p > 0.05$). Still, the total fat of the shoulder, rib and loin varied between treatments ($p < 0.05$) and always with higher amounts of fat in 19.9% of peNDF inclusion and the lowest for the 30.0% of peNDF treatment, the same occurring for subcutaneous and intermuscular fat of the rib and subcutaneous fat of the loin (Table 8). The bone and muscle weights in the commercial cuts were not affected by the peNDF level ($p > 0.05$). However, the shoulder, ribs, and loin fat content decreased linearly ($p < 0.05$) with rising peNDF levels. Similarly, intermuscular fat in the ribs and subcutaneous fat in both the ribs and the loin were reduced considering the orthogonal contrast.

The tissue yield of the shoulder and loin did not vary with the treatments ($p > 0.05$). The treatments affected the tissue composition of the neck, rib, and leg. The muscle yield of the neck was lowest (60.88%) in the treatment with 30.0% of peNDF inclusion and highest (66.66%) in the treatment with 19.9% of peNDF inclusion. The opposite occurred for bone yield from the same cut, i.e., lowest yield

Table 6 Weights and yields of the main organs and viscera of goats finished on pasture and supplemented with different proportions of physically effective fiber (peNDF)

Variables	Physically effective fiber (peNDF, %DM)				SEM[a]	*p*-value[b]	
	19.9	23.3	26.7	30.0		Linear	Quadratic
Weights (kg)							
Rumen	0.545	0.567	0.543	0.525	0.021	0.673	0.655
Reticulum	0.090	0.090	0.084	0.080	0.004	0.312	0.777
Omasum	0.095	0.085	0.085	0.081	0.004	0.205	0.709
Abomasum	0.099	0.124	0.100	0.262	0.042	0.228	0.429
Small intestine	0.459	0.501	0.502	0.464	0.012	0.891	0.109
Large intestine	0.307	0.342	0.329	0.409	0.031	0.305	0.722
Liver	0.370	0.337	0.322	0.323	0.015	0.263	0.591
Heart	0.121	0.143	0.138	0.140	0.014	0.678	0.733
Kidney	0.068	0.068	0.065	0.061	0.001	0.061	0.459
Mesenteric fat	0.389	0.213	0.200	0.202	0.044	0.154	0.316
Perirenal fat	0.190	0.164	0.075	0.097	0.023	0.075	0.595
Omentum	0.265	0.208	0.129	0.124	0.029	0.051	0.642
Yields (%)							
Rumen	5.320b	6.051ab	6.066ab	6.339a	0.142	0.012	0.375
Reticulum	0.878	0.995	0.941	0.944	0.030	0.604	0.361
Omasum	0.933	0.943	0.972	0.970	0.041	0.713	0.944
Abomasum	0.958	1.289	1.116	1.167	0.337	0.130	0.418
Small intestine	4.557	5.522	5.707	5.804	0.243	0.069	0.358
Large intestine	2.998	3.692	3.693	4.891	0.359	0.076	0.721
Liver	3.613	3.641	3.671	3.918	0.146	0.482	0.720
Heart	1.172	1.546	1.510	1.570	0.120	0.291	0.525
Kidney	0.684	0.756	0.743	0.754	0.026	0.423	0.582
Mesenteric fat	3.946	2.278	2.332	2.433	0.475	0.301	0.363
Perirenal fat	1.812	1.510	0.868	1.170	0.171	0.094	0.370
Omentum	2.425	2.017	1.413	1.404	0.213	0.052	0.630

[a]SEM = Standard error of the mean; [b]Significant when $p < 0.05$ from polynomial contrast (linear and quadratic)

Means followed by different lowercase letters differ significantly in treatments according to Tukey's test at a 5% significance level

Table 7 Weights and yields of the commercial cuts of goats finished on pasture and supplemented with different proportions of physically effective fiber (peNDF)

Variables	Physically effective fiber (peNDF, %DM)				SEM[a]	*p*-value[b]	
	19.9	23.3	26.7	30.0		Linear	Quadratic
Weights (kg)							
Half carcass	5.244	4.851	4.602	4.268	0.457	0.117	0.948
Neck	0.743	0.6387	0.6310	0.5057	0.081	0.051	0.896
Shoulder	1.018	0.9410	0.9047	0.8997	0.088	0.311	0.680
Side rib	1.377	1.332	1.1787	1.068	0.145	0.095	0.818
Loin	0.581a	0.532a	0.4562b	0.4451b	0.042	0.018	0.610
Leg	1.526	1.407	1.432	1.343	0.141	0.396	0.913
Yield on cold carcass (%)							
Neck	13.99	13.32	13.69	11.76	1.143	0.215	0.583
Shoulder	19.41b	19.47b	19.70b	21.12a	0.379	0.005	0.081
Side rib	26.27	26.81	25.65	25.05	0.991	0.275	0.563
Loin	11.22	11.29	9.81	10.89	0.729	0.459	0.498
Leg	29.11	29.11	31.15	31.17	0.649	0.009	0.990

[a]SEM = Standard error of the mean; [b]Significant when $p < 0.05$ from polynomial contrast (linear and quadratic);

Means followed by different lowercase letters differ significantly in treatments according to Tukey's test at a 5% significance level

Table 8 Weights of the cuts tissues of goats finished on pasture and supplemented with different proportions of physically effective fiber (peNDF)

Tissue weight (g)	Physically effective fiber (peNDF, %DM)				SEM[a]	*p*-value[b]	
	19.9	23.3	26.7	30.0		Linear	Quadratic
Neck (g)							
Reconstituted neck	693.00	598.67	584.67	555.00	66.08	0.146	0.622
Muscle	471.33	391.33	371.67	341.33	52.39	0.082	0.633
Bone	196.00	187.30	198.00	191.67	13.61	0.968	0.931
Total fat	25.67	20.00	15.00	22.00	5.02	0.481	0.213
Subcutaneous fat	9.33	9.00	7.00	11.00	2.67	0.800	0.419
Intermuscular fat	16.33	11.00	8.00	11.00	2.68	0.131	0.127
Palette (g)							
Reconstituted palette	986.67	905.00	877.33	858.00	85.14	0.268	0.711
Muscle	680.67	620.00	602.00	600.33	64.56	0.359	0.644
Bone	225.33	215.00	220.33	204.33	14.83	0.375	0.847
Total fat	80.67a	70.00a	55.00b	53.33b	10.84	0.040	0.677
Subcutaneous fat	41.33	44.33	32.00	28.00	8.95	0.189	0.694
Intermuscular fat	39.33	25.67	23.00	25.33	7.53	0.189	0.289
Costilhar (g)							
Reconstituted contillar	1302.67	1264.66	1098.67	1016.67	141.66	0.103	0.880
Muscle	804.00	755.67	675.00	647.66	100.31	0.212	0.916
Bone	341.67	363.66	332.67	297.33	32.33	0.257	0.374
Total fat	159.00a	145.33ab	91.00ab	71.67b	26.11	0.010	0.912
Subcutaneous fat	65.33a	56.00ab	49.33ab	26.67b	10.34	0.011	0.517
Intermuscular fat	93.67a	89.33a	45.00b	41.67b	18.62	0.027	0.841
Loin (g)							
Reconstituted loin	551.67	506.33	440.33	435.00	40.39	0.025	0.619
Muscle	363.33	315.00	290.67	286.33	30.29	0.630	0.465
Bone	102.00	121.67	89.00	91.33	13.40	0.297	0.534
Total fat	86.33a	69.67b	60.67b	57.33b	9.12	0.023	0.462
Subcutaneous fat	70.00a	53.00b	52.00b	48.33b	6.81	0.038	0.331
Intermuscular fat	16.33	16.67	8.67	9.00	3.96	0.096	0.998
Leg (g)							
Reconstituted leg	1484.67	1362.00	1391.00	1308.17	138.23	0.407	0.884
Muscle	1075.67	972.33	982.67	927.17	109.00	0.361	0.825
Bone	336.67	323.33	356.33	328.33	23.48	0.938	0.758
Total fat	72.33	66.33	52.00	52.67	10.79	0.128	0.756
Subcutaneous fat	47.33	45.33	29.67	34.67	7.82	0.131	0.659
Intermuscular fat	25.00	21.00	22.33	18.00	5.27	0.393	0.974

[a]SEM = Standard error of the mean; [b]Significant when $p < 0.05$ from polynomial contrast (linear and quadratic);

Means followed by different lowercase letters differ significantly in treatments according to Tukey's test at a 5% significance level

(29.73%) in the treatment with 19.9% of peNDF inclusion and highest (34.97%) in the treatment with 30.0% of peNDF inclusion (Table 9). The rib section was the only cut in which there was variation ($p < 0.05$) in the yield of total fat, subcutaneous fat, and intermuscular fat, with values of 11.99, 4.98, and 7.00% obtained for the 19.9% of peNDF inclusion, exceeding the 6.82, 2.52, and 4.31% observed for the 30.0% of peNDF inclusion.

When evaluating the tissue yield of the commercial cuts (Table 9), from the polynomial contrast, linear effects ($p < 0.05$) were observed on the bone yield of the neck and leg, muscle yield of the neck,

Table 9 Yields of the cuts tissues of goats finished on pasture and supplemented with different proportions of physically effective fiber (peNDF)

Tissue yields (%)	Physically effective fiber (peNDF, %DM)				SEM[a]	*p*-value[b]	
	19.9	23.3	26.7	30.0		Linear	Quadratic
Neck (%)							
Muscle	66.66a	65.00a	63.43ab	60.88b	1.56	0.001	0.773
Bone	29.73b	32.03ab	33.99ab	34.97a	1.65	0.020	0.688
Total fat	3.61	2.97	2.59	4.15	0.60	0.664	0.078
Subcutaneous fat	1.31	1.29	1.19	2.07	0.33	0.155	0.182
Intermuscular fat	2.30	1.68	1.40	2.08	0.35	0.566	0.074
Palette (%)							
Muscle	68.78	68.45	68.33	69.38	0.90	0.670	0.436
Bone	23.05	24.30	25.21	24.25	0.85	0.244	0.198
Total fat	8.17	7.26	6.46	6.37	0.88	0.113	0.641
Subcutaneous fat	4.18	4.60	3.67	3.29	0.72	0.262	0.583
Intermuscular fat	3.98	2.66	2.80	3.07	0.74	0.436	0.282
Costilhar (%)							
Muscle	61.02	59.02	61.23	62.97	1.75	0.310	0.288
Bone	26.99	30.18	30.20	30.21	2.01	0.279	0.427
Total fat	11.99a	10.79a	8.57ab	6.82b	1.24	0.003	0.821
Subcutaneous fat	4.98a	4.10a	4.50a	2.52b	0.53	0.009	0.330
Intermuscular fat	7.00a	6.69a	4.07b	4.31b	1.10	0.037	0.808
Loin (%)							
Muscle	62.28	62.53	65.99	65.30	2.09	0.707	0.628
Bone	18.99	24.01	20.04	21.44	2.19	0.737	0.430
Total fat	15.73	13.46	13.98	13.26	1.39	0.266	0.578
Subcutaneous fat	12.81	10.31	11.73	11.25	1.01	0.483	0.337
Intermuscular fat	2.92	3.16	2.25	2.02	0.78	0.294	0.763
Leg (%)							
Muscle	72.18	71.25	70.38	70.07	0.91	0.078	0.734
Bone	22.91b	24.21a	25.82a	25.84a	0.94	0.018	0.499
Total fat	4.91	4.55	3.80	4.10	0.52	0.175	0.523
Subcutaneous fat	3.16	3.12	2.12	2.69	0.37	0.162	0.429
Intermuscular fat	1.75	1.43	1.68	1.41	0.37	0.639	0.939

[a]SEM = Standard error of the mean; [b]Significant when $p < 0.05$ from polynomial contrast (linear and quadratic);

Means followed by different lowercase letters differ significantly in treatments according to Tukey's test at a 5% significance level

and fat yield in the ribs, in response to the peNDF levels in the supplement.

Discussion

The reduction in pasture intake and total dry matter intake (DMI) observed with increasing levels of physically effective neutral detergent fiber (peNDF) in the supplement demonstrates the inverse relationship between dietary fiber concentration and nutrient intake, even under conditions of abundant forage availability. Although pasture dry matter supply exceeded five times the animals' requirements, intake was primarily constrained by forage quality rather than quantity, as previously reported for grazing small ruminants in semiarid environments (Pulina et al. 2013; Giger-Reverdin et al. 2020). The high NDF concentration of the selected forage (662 g/kg DM), as indicated by extrusa analysis, suggests that ruminal fill and physical limitations imposed by fiber were the dominant factors regulating intake (Emerenciano Neto et al. 2020).

This response is consistent with the established concept that elevated peNDF levels reduce intake by increasing rumen fill and decreasing digesta passage rate (Chizzotti and Chizzotti 2013; Van Soest 1994). The inclusion of malva hay in the supplement,

characterized by high peNDF concentration, likely intensified these effects, even though the material was ground and homogeneously mixed with other ingredients to ensure complete consumption. Consequently, physical constraints on intake reduced the animals' ability to meet energy requirements, leading to lower average daily gain and total weight gain.

The decline in animal performance must also be interpreted considering forage quality dynamics. Despite high dry matter availability, forage quality deteriorated over time, resulting in diets with greater structural fiber and lower energy density (Emerenciano Neto et al. 2018). The combined contribution of fiber from pasture and supplement, together with reduced inclusion of starch-rich ingredients such as corn, likely limited microbial activity and nutrient digestibility, impairing ruminal fermentation efficiency (Osuga et al. 2012; Silva et al. 2014). High-fiber, low-digestibility diets are known to depress microbial growth and fermentation, particularly under tropical grazing conditions (Direkvandi et al. 2020; Veloso et al. 2023).

Dry matter intake expressed as a percentage of body weight (2.26–2.57% BW) was within the range reported for tropical goat breeds (Devendra and Burns 1983) but below NRC (2007) recommendations for intact males targeting 150 g/day of gain. This discrepancy reflects both physical limitations to intake and the inherent characteristics of caatinga vegetation, which exhibits structural and chemical defense mechanisms that restrict consumption and digestibility (Santos et al. 2009). Although the haymaking process can partially mitigate these effects by reducing volatile antinutritional compounds, including tannins (Pereira Filho et al. 2013; Oliveira et al. 2025), residual phenolic compounds may still impair ruminal microbial activity when present at elevated concentrations (Gemeda and Hassen 2015; Inô et al. 2024).

Consistent with this interpretation, tannin-rich diets have been associated with reduced dry matter intake and potentiation of the negative effects of high dietary peNDF (Naumann et al. 2017). Similar intake depressions have been reported in small ruminants consuming caatinga forages with NDF concentrations above 450 g/kg DM (Gama et al. 2020; Da Silva Aguiar et al. 2023). Although crude protein (CP) intake did not differ statistically among treatments, numerically lower CP intake at higher peNDF levels reflected both reduced DMI and potential increases in fiber-bound protein fractions, limiting ruminal nitrogen availability. Observed CP intakes (58–79 g/day) were below NRC (2007) recommendations, likely impairing microbial protein synthesis and further constraining animal performance.

From a carcass perspective, the absence of treatment effects on hot and cold carcass weights, coupled with reduced carcass yields, indicates greater gastrointestinal fill and increased ruminal content at higher peNDF levels. The linear increase in rumen yield supports this hypothesis and reflects prolonged ruminal retention time and enhanced rumen wall development associated with fibrous diets (Mertens 1997; Animut et al. 2005). Reduced fat deposition and increased non-carcass components further contributed to lower dressing percentages (Mariz et al. 2013; Silva et al. 2015).

Among commercial cuts, only loin weight declined with increasing peNDF, suggesting insufficient energy supply for muscle deposition in metabolically demanding regions (Nobrega et al. 2013). In contrast, increased yields of the shoulder and leg indicate a redistribution of muscle tissue toward cuts with earlier physiological development and lower energy demand (Pereira Filho et al. 2013). The reduction in subcutaneous and intermuscular fat, particularly in ribs and loin, reinforces the central role of dietary energy in lipogenesis and carcass finishing (Marques et al. 2014). These effects are consistent with allometric growth patterns, whereby fat and later-maturing tissues are most sensitive to nutritional restriction (Cezar and Sousa 2007; Kannan et al. 2006).

The marked reduction in internal fat depots, especially omental fat, further confirms a systemic limitation in energy availability for non-essential tissue deposition under high peNDF diets (Brand et al. 2019). While moderate peNDF inclusion is essential for rumen function, excessive levels (> 23–25% of supplement DM) appear detrimental to intake, growth, and carcass quality in finishing goats grazing semiarid pastures.

From a production standpoint, the inclusion of native forages such as malva hay represents a cost-effective and regionally adapted feeding strategy. However, careful attention must be given to fiber digestibility, particle size, and antinutritional factors to avoid compromising animal performance (Villalba et al. 2021). Overall, moderate peNDF inclusion optimizes the balance between ruminal health, energy

utilization, and desirable carcass traits, ensuring adequate fat deposition for meat quality, consumer acceptance, and market value (Queiroz et al. 2021; Schumacher et al. 2022).

Conclusion

Supplementation with peNDF levels ranging from 19.9% to 30% of total dry matter of the F1 crossbred goats (Boer×Creole) fed on tropical pastures in the Caatinga biome, provided at 1.5% of body weight, does not affect intake, digestibility, feed efficiency, or the yield of viscera and organs in finishing goats on pasture. The optimal use (up to 23%) of physically effective fiber (peNDF) from tropical forages enhances the utilization of Caatinga resources and can reduce the need for concentrated feeds. However, when peNDF levels exceed 23% of total dry matter, there is a reduction in dry matter intake, weight gain, and carcass yield. The observed increase in rumen weight at higher peNDF levels suggests that moderate supplementation (up to 23% DM) may support rumen development during earlier growth phases. Nonetheless, high-peNDF diets are not recommended during the finishing stage, when energy efficiency, muscle accretion, and optimal fat deposition in commercially valuable cuts are priorities.

Author contributions JMPF, MFC and LRB conceived and designed the study. CIST, JNAW and LSS conducted data gathering. MAC and LSS conducted the laboratory analyses. JMPF, JFPM and JPFO performed statistical analyses. LSS, JMPF, LSS and GAP wrote the article. All authors have read and agree to submit the manuscript.

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing financial interests or personal relationships that could have influenced the study reported in this paper.

Ethics approval All procedures followed the guidelines recommended by the National Ethical Committee for the Control of Animal Experimentation (CONCEA, Brazil) for the use of fistulated animals (Approval Protocol Number 264/2015).

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References

Animut G, Goetsch AL, Aiken GE, Puchala R, Detweiler G, Krehbiel CR, Estell RE (2005) Grazing behavior and energy expenditure by sheep and goats co-grazing grass/forb pastures at three stocking rates. Small Rumin Res 59:191–201. https://doi.org/10.1016/j.smallrumres.2005.05.014

Association of Official Analytical Chemists (2015) Official methods of analysis, 19th edn. AOAC International, Washington, DC

Balehegn M, Ayantunde A, Amole T, Njarui D, Nkosi BD, Müller FL, Meeske R, Tjelele TJ, Malebana IM, Madibela OR, Boitumelo WS, Lukuyu B, Weseh A, Minani E, Adesogan AT (2022) Forage conservation in sub-Saharan Africa: review of experiences, challenges, and opportunities. Agron J 114:75–99. https://doi.org/10.1002/agj2.20954

Bandeira PAV, Pereira Filho JMP, Silva AMA, Nóbrega GH, Ribeiro RDX, Cardoso DB, Madruga MS (2017) Performance and carcass characteristics of lambs fed diets with increasing levels of *Mimosa tenuiflora* (Willd.) hay replacing Buffel grass hay. Trop Anim Health Prod 49:1001–1007. https://doi.org/10.1007/s11250-017-1291-y

Brand TS, Van Der Merwe DA, Swart E, Hoffman LC (2019) The effect of finishing period and dietary energy content on the carcass characteristics of Boer goats. Small Rumin Res 174:110–117. https://doi.org/10.1016/j.smallrumres.2019.03.012

Cézar MF, Sousa WH (2007) Carcaças ovinas e caprinas: obtenção–avaliação–classificação. Editora Agropecuária Tropical, Uberaba

Chizzotti ML, Chizzotti FHM (2013) Consumo e digestibilidade de plantas forrageiras. In: Reis RA, Bernardes TF, Siqueira GR (eds) Forragicultura: ciência, tecnologia e gestão dos recursos forrageiros, 1st edn. FUNEP, Jaboticabal, p 714

da Silva Aguiar F, Bezerra LR, Cordão MA, Cavalcante ITR, Oliveira JPF, Nascimento RRD, Souza BB, Oliveira RL,

Pereira ES, Pereira Filho JM (2023) Effects of increasing levels of total tannins on intake, digestibility, and balance of nitrogen, water, and energy in hair lambs. Animals 13:2497. https://doi.org/10.3390/ani13152497

de Lima Júnior V, da Silva DS, Marques CAT, da Costa Torreão JN, Gurgel ALC, Dias-Silva TP, Batista ÂMV (2025) Goat supplementation in dry tropical agroforestry: assessment of methodologies for estimation of nutrient intake. Agroforest Syst 99:168. https://doi.org/10.1007/s10457-025-01269-7

Devendra C, Burns M (1983) Goat production in the tropics, 2nd edn. Commonwealth Agricultural Bureaux, Surrey

Direkvandi E, Mohammadabadi T, Salem AZM (2020) Effect of microbial feed additives on growth performance, microbial protein synthesis, and rumen microbial population in growing lambs. Transl Anim Sci 4:txaa203. https://doi.org/10.1093/tas/txaa203

Emerenciano Neto JV, Difante GS, Lana AMQ, Medeiros HR, Aguiar EM, Montagner DB, Souza JS (2018) Forage quality and performance of sheep in Massai grass pastures managed at pre-grazing canopy heights. S Afr J Anim Sci 48:1073–1081. https://doi.org/10.4314/sajas.v48i6.10

Emerenciano Neto JV, Medeiros HR, Pereira ES, Silva RB, Silva CS, Nascimento MSCB (2020) Cultivated pastures affect nutrient intake and feeding behavior of sheep. Trop Anim Sci J 43:117–124. https://doi.org/10.5398/tasj.2020.43.2.117

Formiga LDAS, Pereira Filho JM, Oliveira NS, Silva AMA, Cézar MF, Soares DC (2011) Nutritive value of herbaceous vegetation of caatinga enriched and grazed by sheep and goats. Rev Bras Saude Prod Anim 12:403–415

Gama KVMF, Pereira Filho JM, Soares RF, Cordão MA, Cézar MF, Batista ASM, Bezerra LR (2020) Fatty acid, chemical, and tissue composition of meat comparing Santa Inês breed sheep and Boer crossbreed goats submitted to different supplementation strategies. Trop Anim Health Prod 52:601–610. https://doi.org/10.1007/s11250-019-02047-1

Gemeda BS, Hassen A (2015) Effect of tannin and species variation on in vitro digestibility, gas, and methane production of tropical browse plants. Asian-Australas J Anim Sci 28:188–199. https://doi.org/10.5713/ajas.14.0325

Giger-Reverdin S, Domange C, Broudiscou LP, Sauvant D, Berthelot V (2020) Rumen function in goats, an example of adaptive capacity. J Dairy Res 87:45–51. https://doi.org/10.1017/S0022029920000060

Inô CFA, Pereira Filho JM, Oliveira RMT, Oliveira JFP, Silva Filho EC, Nascimento AMSS, Oliveira RL, Nascimento RR, Lucena KHOS, Bezerra LR (2024) New technology of rumen-protected bypass lysine encapsulated in lipid matrix of beeswax and carnauba wax and natural tannin blended for ruminant diets. Anim 14:2895. https://doi.org/10.3390/ani14192895

Kannan G, Gadiyaram KM, Galipalli S, Carmichael A, Kouakou B, Pringle TD, McMillin KW, Gelaye S (2006) Meat quality in goats as influenced by dietary protein and energy levels, and postmortem aging. Small Rumin Res 61(1):45–52. https://doi.org/10.1016/j.smallrumres.2005.01.006

Kononoff PJ, Heinrichs AJ, Buckmaster DR (2003) Modification of Penn State forage and total mixed ration particle separator and the effects of moisture content on its measurements. J Dairy Sci 86(5):1858–1863. https://doi.org/10.3168/jds.S0022-0302(03)73773-4

Lammers BP, Buckmaster DR, Heinrichs AJ (1996) A simple method for the analysis of particle sizes of forage and total mixed rations. J Dairy Sci 79:922–928. https://doi.org/10.3168/jds.S0022-0302(96)76442-1

Licitra G, Hernandez TM, Van Soest PJ (1996) Standardization of procedures for nitrogen fractionation of ruminant feeds. Anim Feed Sci Technol 57(4):347–358. https://doi.org/10.1016/0377-8401(95)00837-3

Mariz LDS, Valadares Filho SC, Detmann E, Paulino MF, Valadares RFD, Silva BC (2013) Intake and ruminal digestion determined using omasal and reticular digesta samples in cattle fed diets containing sugar cane in natura or ensiled sugar cane compared with maize silage. Livest Sci 155:71–76. https://doi.org/10.1016/j.livsci.2013.04.003

Marques AAT, Medeiros AN, Costa RG, Carvalho FFR, Araújo MJ, Torreão JNC (2014) Performance and carcass traits of Moxotó growing goats supplemented on native pasture under semiarid conditions. R Bras Zootec 43:151–159. https://doi.org/10.1590/S1516-35982014000300008

Mertens DR (1997) Creating a system for meeting the fiber requirements of dairy cows. J Dairy Sci 80:1463–1481. https://doi.org/10.3168/jds.S0022-0302(97)76075-2

National Research Council (2007) Nutrient requirements of small ruminants, 7th edn. National Academic Press, Washington, DC, USA

Naumann HD, Tedeschi LO, Zeller WE, Huntley NF (2017) The role of condensed tannins in ruminant animal production: advances, limitations and future directions. Rev Bras Zootec 46:929–949. https://doi.org/10.1590/S1806-92902017001200009

Nobrega GH, Cézar MM, Pereira Filho JM, Sousa WH, Sousa OB, Cunha MGG, Santos JRS (2013) Diet for compensatory gain of feedlot lambs: commercial composition of carcass cuts and tissues. Arq Bras Med Vet Zootec 65:469–476. https://doi.org/10.1590/S0102-09352013000200024

Oliveira RM, Pereira Filho JM, Inô CFA, Andrade E, Lucena KH, Oliveira JP, Pereira E, Oliveira RL, Edvan RL, Bezerra LR (2025) Microencapsulated escape lysine with tannin as an adjuvant in sheep diets. Vet Sci 12:14. https://doi.org/10.3390/vetsci12010014

Osuga IM, Abdulrazak SA, Muleke CI, Fujihara T (2012) Effect of supplementing rhodes grass hay (*Chloris gayana*) with *Berchemia discolor* or *Zizyphus mucronata* on the performance of growing goats in Kenya. J Anim Physiol Anim Nutr 96:634–639. https://doi.org/10.1111/j.1439-0396.2011.01189.x

Pereira Filho JM, Silva AMA, Cezar MF (2013) Management of the Caatinga for the production of goats and lambs. Rev Bras Saude Prod Anim 14:77–90

Pulina G, Avondo M, Molle G, Francesconi AHD, Atzori AS, Cannas A (2013) Models for estimating feed intake in small ruminants. Rev Bras Zootec 42:675–690. https://doi.org/10.1590/S1516-35982013000900010

Queiroz LO, Barbosa AM, Mourão GB, Fonseca MA, Pinto LFB, Silva Júnior JM, Silva TM, Lima AGVO, Bezerra LR, Oliveira RL (2021) Performance, carcass traits and meat quality of lambs fed with different

roughage:concentrate ratios associated with variable physically effective neutral detergent fibre content. J Agric Sci 159:293–303. https://doi.org/10.1017/S0021859621000459

Salem HB, Smith T (2008) Feeding strategies to increase small ruminant production in dry environments. Small Rumin Res 77:174–194. https://doi.org/10.1016/j.smallrumres.2008.03.008

Saliba EOS (2005) Uso de indicadores: passado, presente e futuro. In: Anais da Teleconferência Sobre Indicadores em Nutrição Animal. Edn. UFMG, Escola de Veterinária da Universidade Federal de Minas Gerais, Belo Horizonte, pp 4–22

Santos GRA, Batista ÂMV, Guim A, Santos MVF, Silva MJA, Pereira VLA (2008) Evaluation of botanical composition of sheep diet in Caatinga pasture. Rev Bras Zootec 37:1876–1883. https://doi.org/10.1590/S1516-35982008001000023

Santos GRA, Batista AMV, Guim A, Santos MVF, Matos DS, Santoro KR (2009) Chemical composition and in situ digestibility of diets for sheep in the Caatinga region. Rev Bras Zootec 38:384–391. https://doi.org/10.1590/S1516-35982009000200023

SAS Institute Inc (2004) Statistical Analysis System user's guide. Version 6. SAS Institute Inc., Cary, NC, USA, p 956

Schumacher M, DelCurto-Wyffels H, Thomson J, Boles J (2022) Fat deposition and fat effects on meat quality—a review. Animals 12:1550. https://doi.org/10.3390/ani12121550

Senger CC, Kozloski GV, Sanchez LMB, Mesquita FR, Alves TP, Castagnino DS (2008) Evaluation of autoclave procedures for fibre analysis in forage and concentrate feedstuffs. Anim Feed Sci Technol 146:169–174. https://doi.org/10.1016/j.anifeedsci.2007.12.008

Silva DCD, Guim A, Santos GRA, Mesquita FLTD, Morais NAPD, Urbano SA, Moreira Filho MA, Lafayette EA (2014) Levels of supplementation on quantitative carcass aspects and leg tissue composition of crossbred goats finished on Caatinga. Rev Bras Saude Prod Anim 15:705–716

Silva DL, Oliveira KP, Aroeira LJ, Chaves DF, Ponciano MF, Braga AP, Júnior DML (2015) Chemical composition of Caatinga potential forages species. Trop Subtrop Agroecosyst 18:267–272

Soares RF, Pereira Filho JM, Gama KVMF, Silva AMA, Cezar MF, Ramos JM, Borburema JB, Bakke OA (2016) Performance of sheep and goats finished in enriched Caatinga and given supplementation. Livest Res Rural Dev 28:1

Tikam K, Phatsara C, Sorachakula C, Vearasilp T, Samiprem S, Cherdthong A, Gerlach K, Südekum KH (2014) In vitro gas production, in vivo nutrient digestibilities, and metabolisable energy concentrations for sheep of fresh and conserved pangola grass. Small Rumin Res 128:34–40. https://doi.org/10.1016/j.smallrumres.2015.05.002

Van Soest PJ, Robertson JB, Lewis BA (1991) Methods for dietary fibre, neutral detergent fibre, and non-starch polysaccharides in relation to animal nutrition. J Dairy Sci 74:3583–3597. https://doi.org/10.3168/jds.S0022-0302(91)78551-2

Van Soest PJ (1994) Nutritional ecology of the ruminant. Cornell University Press, Ithaca

Veloso ACR, Lopes HF, Santos LFX, Martins Junior VS, Fonseca SA, Santos TAX, Matias AD, Careli RT, Duarte ER, Braz TGS (2023) Elephant grass silage inoculated with cellulolytic fungi isolated from rumen. Arq Bras Med Vet Zootec 75:981–992. https://doi.org/10.1590/1678-4162-12984

Villalba JJ, Ates S, MacAdam JW (2021) Non-fiber carbohydrates in forages and their influence on beef production systems. Front Sustain Food Syst 5:566338. https://doi.org/10.3389/fsufs.2021.566338

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