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GHG production and energy partitioning in female and male Somali sheep under different diets

Abstract – The objective of this work was to evaluate greenhouse gas (GHG) production and energy partitioning in growing female and male Brazilian Somali sheep subjected to different diets. The experiment was completely randomized, in a 3×2 (three diets combining crude protein and total digestible nutrients x sex classes) factorial arrangement, with four replicates. The factorial analysis of variance was used, and means were compared by Tukey's test. GHG emissions and energy partitioning were determined using open-circuit respirometry chambers. No effect of sex was observed. Sheep fed the diet that met 100% of the recommendations of National Research Council (NRC) showed a higher gross energy intake, digestible energy intake, oxygen consumption, carbon dioxide production, heat production, and respiratory quotient than sheep fed the diet that met only 85%. However, both diets showed similar results for gross energy loss via feces, metabolizable energy intake, energy balance, metabolizability, metabolizable:digestible energy ratio, and daily methane production. The net energy requirement of Brazilian Somali sheep did not differ between sex classes during their early growth phase. At this phase, the diet that met 85% of the NRC recommendations can be used instead of the one that met 100%, without reducing energy efficiency or increasing methane emissions.

Index terms: calorimetry, energy balance, feed intake, respiratory metabolism, semi-arid zones.

Produção de GEE e partição de energia em fêmeas e machos de ovinos somalis brasileiros sob diferentes dietas

Resumo – O objetivo deste trabalho foi avaliar a produção de gases de efeito estufa (GEE) e a partição de energia em fêmeas e machos de ovinos da raça somalis brasileira, em crescimento, submetidos a diferentes dietas. O experimento foi em delineamento inteiramente casualizado, em esquema fatorial 3×2 (três dietas combinando proteína bruta e nutrientes digestíveis totais x sexos), com quatro repetições. Utilizou-se a análise de variância fatorial, e compararam-se as médias com o teste de Tukey. As emissões de GEE e a partição de energia foram determinadas com uso de câmaras de respirometria em circuito aberto. Não foi observado efeito do sexo. As ovelhas alimentadas com a dieta que atendia 100% das recomendações do National Research Council (NRC) apresentaram maior ingestão bruta de energia, ingestão de energia digestível, consumo de oxigênio, produção de dióxido de carbono, produção de calor e quociente respiratório do que as que receberam a dieta que atendia 85%. No entanto, ambas as dietas

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apresentaram resultados semelhantes para perda bruta de energia via fezes, ingestão de energia metabolizável, balanço energético, metabolizabilidade, relação energia metabolizável:energia digestível e produção diária de metano. A necessidade líquida de energia dos ovinos da raça somalis brasileira não diferiu entre os sexos durante a fase inicial de seu crescimento. Nessa fase, a dieta que atingiu 85% das recomendações do NRC pode ser utilizada em vez da que atingiu 100%, sem reduzir a eficiência energética ou aumentar as emissões de metano.

Termos para indexação: calorimetria, balanço energético, consumo alimentar, metabolismo respiratório, zonas semiáridas.

Introduction

The National Research Council (NRC) recommends diet formulations that are mostly based on nutritional requirements and feeding information adequate to a temperate climate, which may not accurately reflect the needs of animals raised in a tropical climate (Oliveira et al., 2018). Even in a temperate climate, updates are necessary (Yang et al., 2020), as shown in a study with sheep carried out in the United Kingdom, which highlighted that feed recommendations by Agricultural and Food Research Council and NRC were developed using data obtained more than 40 years ago (Alderman, 1993).

In relation to the recommendations of NRC, Deng et al. (2014), for example, found a lower net energy and metabolizable energy for Dorper crossbred ewe lambs. According to a meta-analysis in 2014, this could be due to changes in the energy and protein requirements of sheep, goats, and cattle in warm climates, requiring new feeding standards (Salah et al., 2014). However, for a nondescript breed of hair lambs in the semiarid climate of Brazil, Rodrigues et al. (2016) observed energy and protein requirements near the values recommended by NRC. Contrastingly, Carvalho et al. (2021), evaluating the nutritional value of ingested native forage species of the Caatinga, detected reductions of 15% in the levels of crude protein (CP) and total digestible nutrients (TDN) between the rainy season and the rainy-dry transition period. These results suggest that current sheep flocks with a high genetic merit may have higher energy requirements for maintenance than those presently recommended.

In this context, understanding the nutritional needs of animals raised in warm climates is key to optimize feed and nutrient use, reduce production costs, improve feed efficiency, and, consequently, reduce greenhouse gas (GHG) emissions.

In Brazil, the Brazilian Somali, Santa Inês, and Morada Nova breeds are examples of sheep genetic groups that have been evaluated due to their local adaption to the country's semiarid climate and wide use in industrial crossbreeding with exotic breeds (Ribeiro & González-Garcia, 2016). Studying Brazilian Somali lambs, Fontenele (2014) obtained a net energy maintenance requirement of 45.63 kcal kg body weight $(BW)^{-0.75}$, lower than the values recommended by NRC (2007) and Commonwealth Scientific and Industrial Research Organisation (CSIRO, 2007). According to Figueiredo (2018), an important characteristic of this breed is that it accumulates fat in the rump during periods of abundant feeding, which is used as an energy source when there is food scarcity.

For the production of crossbred Santa Inês sheep in a grazing system in the Caatinga biome, Costa (2016) reported an average CH_4 production of 16.9 g per day per animal, which varied according to the availability and quality of biomass in the pasture. In another work with Santa Inês lambs, the average CH_4 production was 13.06 g per day per animal raised in a confinement production system (Costa, 2021). These findings suggest that GHG emissions can be reduced due to feed quality.

The performance of cattle production can be successfully optimized using respirometry (Machado et al., 2016). This technique is also suitable for measuring GHG emissions from smaller ruminants and their metabolism in the Caating biome (Rogério et al., 2019). Respirometry is the gold standard measure of mitochondrial oxidative function, as it reflects the activity of electron transport chain complexes in a combined manner (Acin-Perez et al., 2020).

In the present study, the focus was on the Brazilian Somali breed, considering that this hair sheep used for meat production is well adapted to the Brazilian semiarid climate (Lima, 2017). The hypotheses are that different nutritional plans may affect the energy requirements of noncastrated males and females of the breed, and that the daily GHG production in sheep will decrease with a 15% reduction in CP and TDN compared with the values recommended by NRC (2007).

The objective of this work was to evaluate GHG production and energy partitioning in growing female and male Brazilian Somali sheep subjected to different diets.

Materials and Methods

The experiment was conducted at the Semiarid Respirometry Laboratory of Embrapa Caprinos e Ovinos, in the municipality of Sobral, in the state of Ceará, Brazil (3º41"S, 40º20"W). The region has a BSh climate according to Köppen's classification. Chemical and bromatological analyses were performed at the Animal Nutrition Laboratories of Embrapa Caprinos e Ovinos and of Universidade Federal do Ceará. All procedures were approved by the ethics committee on the use of animals of Embrapa Caprinos e Ovinos, under protocol number 001/2017.

For the study, 24 four-month-old sheep were divided into two groups: 12 noncastrated males, with a mean BW of 15.40±3.21 kg; and 12 females, with a mean BW of 14.86±2.50 kg. The experimental unit was considered one sheep.

The experimental design was completely randomized, in a 3×2 factorial arrangement (three diets combining CP and TDN x two sex classes – noncastrated males and females), with four replicates. The diets were formulated according to the recommendations of NRC (2007), as follows: maintenance diet (M-NRC), based on the recommended maintenance requirements; 100% of the recommended (100 - NRC), a diet based on 100% of the recommendations of NRC for CP and TDN; and 85% of the recommended (85 - NRC), a diet based on 85% of the recommendations of NRC for CP and TDN. These recommendations assume a sheep at early maturity, with a 20 kg BW and a mean daily gain of 200 g per day.

The adaptation period to the environment and experimental diets lasted 14 days. The diets were offered twice a day, at 8 a.m. and 4 p.m., allowing for up to 5% feed refusal based on the amount offered. The chemical and proximate composition of the diets are presented in Table 1.

GHG emissions and energy partitioning were determined using two open-circuit respirometry chambers, in which air temperature and relative humidity were set to 25.0±1.5°C and 70±5%, respectively. A set of equipment from Sable International System (Las Vegas, NV, USA) were used: the FK-100 FlowKit mass flow meter, the CA-10 Carbon Dioxide Analyzer, the MA-10 Methane Analyzer, and the FC-10 Oxygen Analyzer, all connected to a system for data acquisition, processing, and recording. The used methodology was that of Rodríguez et al. (2007). Calibration procedures were performed according to Machado et al. (2016) and Rogério et al. (2019).

The animals were weighed before being placed inside the respirometry chambers. Two animals were evaluated per day, one in each chamber, being monitored for a mean period of 22 hours per day; data extrapolated to a 24 hour period. The day after entering the chambers, the animals were swapped between chambers, and a new reading cycle started. A third measurement was conducted if there were variations above 5% in the production of CO_2 and CH_4, in the consumption of O_2, or in the intake of dry matter in two consecutive days for the same animal. In the days in the chamber, the animals were fed the daily amount of feed at once (Rodríguez et al., 2007), immediately before the chambers were sealed and data were collected.

Heat production (HP, kcal per day) was determined according to Brouwer (1965), as follows:

$$HP = 3.866 \cdot VO_2 + 1.200 \cdot VCO_2 + 0.518 \cdot VCH_4 - 1.431 \cdot Nu$$

where VO_2 is oxygen volume, in liters per day; VCO_2 is the volume of carbon dioxide, in liters per day; VCH_4 is methane gas, also in liters per day; and Nu is the amount of urinary nitrogen, in grams per day. The GHG emissions were estimated using the Tier 2 methodology of Intergovernmental Panel on Climate Change (IPCC, 2006).

Energy partitioning was determined by subtracting the losses of energy through feces, urine, methane, and heat production from gross energy intake. For methane, energy loss was estimated as 9.45 kcal per day per liter of CH_4 produced (Brouwer, 1965).

Diet metabolizability was calculated as the ratio between the intakes of metabolizable energy and gross energy (Alderman, 1993). The values used for the respiratory quotient, related to the type of substrate being metabolized, were those recommended by Kleiber (1972): close to 1.0, 0.7, and 0.8, indicating carbohydrates, fats, and proteins, respectively.

A five-day collection period was used to determine feed intake and digestibility. Refusals and total feces were collected, placed in plastic bags, and weighed. Then, samples of 20% of the refusals and the total daily feces produced were collected, stored in appropriate containers, and put in a freezer, at -10°C, until the laboratory analysis.

Plastic trays were placed below the cage ducts in order to collect urine for evaluation. Every day after the daily urine was removed, 100 mL of hydrochloric acid (HCl 2N) were added to each tray to prevent nitrogen volatilization. The weight and volume of the excreted urine were measured the day after. A sample for urinary nitrogen determination was obtained by spot urine collection (spontaneous urination) using colostomy bags (Medsonda, Arapoti, PR, Brazil). The bags were fixed around the vagina of the females or the penis of the males for subsequent measurement of volume and weight. The material was stored in a freezer, at -10°C, until the laboratory analysis. At the end of the experiment, samples of feed, refusals, and feces were thawed and pre-dried, at 55°C, in a forced-air oven until reaching a constant weight. Then, the samples were ground in a knife-type mill into 1.0 mm particles.

The contents of dry matter, ash or mineral matter, CP, ether extract using the methodology of AOAC International (Horwitz, 2005), neutral detergent fiber, acid detergent fiber, cellulose, hemicellulose, and lignin were determined. Analyses were also carried out for neutral detergent insoluble protein and acid detergent insoluble protein according to Van Soest et al. (1991). Corrections for ash insoluble in neutral detergent were performed according to the standard analytical methods of Instituto Nacional de Ciência e Tecnologia de Ciência Animal (Detmann et al., 2012).

To estimate TDN, the equation proposed by NRC (2001) was used. The percentage of total carbohydrates was calculated according to Sniffen et al. (1992), as:

$$TC\ (\%) = 100 - (CP + EE + AS)$$

Table 1. Proximate and chemical composition of the experimental diets based on the recommendations of National Research Council (NRC, 2007) for crude protein and total digestible nutrients.

Ingredient	Diet[1]		
	M-NRC	85-NRC	100-NRC
Proximate composition (% dry matter)			
Tifton 85 grass hay	74.15	60.09	28.08
Elephant grass hay	25.85	-	-
Corn	-	27.73	56.31
Soybean meal	-	6.55	10.05
Oil	-	5.63	5.11
Limestone	-	-	0.45
Total	100.00	100.00	100.00
Roughage (concentrate ratio)	100:0	60:40	28:72
Chemical composition (g kg^{-1} dry matter)[2]			
Dry matter	935.09	941.21	941.87
Mineral matter	46.15	31.83	25.02
Organic matter	953.85	968.17	974.98
Ether extract	18.11	77.95	75.88
Crude protein	70.28	101.76	120.22
Neutral detergent fiber	784.14	525.29	329.22
NDFap	713.34	492.28	311.83
Acid detergent fiber	424.11	241.70	133.88
NDIP	70.03	53.83	32.21
ADIP	38.64	36.95	36.03
Total carbohydrates	865.46	788.24	774.17
Nonfiber carbohydrates	151.36	316.78	477.17
Total digestible nutrients	422.09	642.98	762.91

[1]M-NRC, diet for maintenance of crude protein and total digestible nutrients; 85-NRC, diet meeting 85% of the recommendations of NRC; and 100-NRC, diet meeting100% of the recommendations of NRC. [2]NDFap, neutral detergent fiber corrected for ash and crude protein; NDIP, neutral detergent insoluble protein; and ADIP, acid detergent insoluble protein.

where TC is total carbohydrates, CP is crude protein, EE is ether extract, and AS is ash content.

The content of nonfiber carbohydrates was obtained according to Hall (2000), as:

$$NFC = 100 - (NDFap + CP + EE + AS)$$

where NFC are nonfiber carbohydrates, NDFap is NDF corrected for ash and CP, EE is ether extract, and AS is ash content.

The gross energy of the offered feed, refusals, feces, and urine samples was determined using the 6100 Compensated Calorimeter (Parr Instrument Company, Moline, IL, USA).

The net energy requirement for maintenance (NE_m) was estimated by the nonlinear relationship between heat production and metabolizable energy intake, according to the following equation:

$$HP = \beta_0 \times e^{\beta_1 \times MEI}$$

where HP is heat production (kcal kg $BW^{-0.75}$); MEI is the daily intake of metabolizable energy; β_0 is the intercept of the equation, when the animal's heat production is at fasting (MEI = 0), corresponding to NE_m; β_1 is the regression parameter without biological meaning; and e is Euler's number.

The metabolizable energy for maintenance (ME_m) was determined using the iterative method to solve the equation for NE_m, assuming the equilibrium point between metabolizable energy intake and heat production. The efficiency of metabolizable energy use (k_m) was obtained through the equation:

$$k_m = ME_m / NE_m$$

The data were subjected to the analysis of influential values and outliers through the Studentized residual analysis. Data with residual values greater than ±2.5 were excluded. Remaining data were checked for assumptions of normality, independence of errors, and homoscedasticity using the tests of Shapiro-Wilk, Durbin-Watson, and Bartlett, respectively. All assumptions were met at α = 0.05. The factorial analysis of variance was performed, and data were analyzed using the MIXED procedure of the SAS statistical software (Edition University, SAS, 2015), with the following equation:

$$Y_{ijk} = \mu + S_i + R_j + S \times R_{ij} + \varepsilon_{ijk}$$

where Y_{ijk} is the dependent variable of experimental unit "k", of sex "i", and under diet "j"; μ is the constant; S_i is the effect of sex "i"; R_j is the effect of dietary recommendation "j"; S x R_{ij} is the interaction effect between sex "i" and dietary recommendation "j"; and ε_{ijk} is the random error. Means were calculated using the LSMEANS SAS' command adjusted for Tukey's test (α=0.05).

Results and Discussion

The interaction between sex and diet, as well as the differences between sex and energy-balance related variables, were nonsignificant (p>0.05). Urinary gross energy was not influenced by sex or diet (p>0.05). However, there were dietary influences (p<0.05) for gross energy intake, fecal gross energy, digestible energy intake, methane gross energy, metabolizable energy intake, and heat production.

Gross energy intake was the highest in sheep subjected to 100-NRC, but the lowest in those fed M-NRC; the same pattern was observed for digestible energy intake and heat production. The highest gross energy intake for sheep fed 100-NRC is likely due to this diet's highest level of nonfiber carbohydrates and TDN (Table 1). According to Cavalcanti et al. (2019), there is a positive correlation of voluntary intake and diet energy content with gross energy intake. Therefore, digestible energy intake reflects energy losses via feces. Sheep fed 100-NRC and 85-NRC showed the highest fecal gross energy, metabolizable energy intake, and energy balance, with similar values at the ages from 4 to 8 months (Table 2).

Given gross energy intake, energy loss through feces was proportionally higher in sheep subjected to 85-NRC (28%) than to 100-NRC (26%). Contrastingly, energy loss through methane production was the highest in M-NRC (8%) and the lowest in 85-NRC (3%) and 100-NRC (3%). In their study, Hook et al. (2010) reported methane energy losses varying from 5 to 12% of gross energy intake. The results obtained in the present study show that the diets with 85 and 100% of NRC recommendations were properly balanced, minimizing methane energy loss. However, 85-NCR is preferred due to the lower gross energy intake compared with that with 100-NCR. Regarding energy balance, negative values were only found for M-NRC, indicating that animals fed it were energy deficient. The high energy balance observed in sheep subjected to 100-NRC and 85-NRC is attributed to a high metabolizable energy intake, indicating a high availability of metabolizable energy after maintenance demands were met (Ferreira et al., 2019).

A high dry matter intake produces more heat due to the energy needed for ingesting and transporting the digesta (Williams et al., 2023). In ruminants, heat production increases as metabolizable energy intake and energy retention also increase (Chizzotti et al., 2008; Martins et al., 2019). This was noted in the present work, where sheep with a high metabolizable energy intake and energy retention showed a high heat production (Table 6). In a study with Brazilian Somali sheep, Pereira et al. (2014) reported that an increased metabolizable energy intake and energy retention resulted in a greater caloric increment.

Metabolizability and the ratio between metabolizable energy and digestible energy (ME/DE) showed a significant difference ($p<0.05$) between M-NRC and 100-NRC and 85-NRC, with the last two not differing from each other. Gross energy digestibility was not affected ($p>0.05$) by sex or diets (Table 3).

The low metabolizability observed for animals fed M-NRC may be related to the low intake of metabolizable energy and gross energy in these animals (Table 2), as well as to the high proportion of roughage in the diet (Table 1), as also observed in Resende et al. (2011). Moreover, 100-NRC and 85-NRC showed higher energy contents, resulting in an increased metabolizability due to the greater use of available energy (Ferrel & Oltjen, 2008).

The higher ME/DE ratio found in 100-NRC and 85-NRC is related to a higher energy density in these diets compared with M-NRC, which showed a lower ratio. Diets with a high amount of energy allow of a greater efficiency in converting digestible energy into metabolizable energy (Galyean et al., 2016; Weiss &

Table 2. Results of mean, standard error of the mean (SEM), and p-values of the effects of sex, diet, and their interaction, as well as mean comparison of energy partitioning, obtained for noncastrated males (MS) and females (FS) of Brazilian Somali sheep fed diets based on the recommendations of National Research Council (NRC, 2007) for crude protein and total digestive nutrients[(1)].

Variable	Sex		Dietary treatment[(2)]			SEM	p-value		
	MS	FS	M-NRC	85-NRC	100-NRC		Sex	Diet	Sex × Diet
Gross energy intake (kcal per day kg $BW^{-0.75}$)	176.93	193.64	81.55 c	216.57 b	257.73 a	20.04	0.1743	< 0.0001	0.3371
Fecal gross energy (kcal kg $BW^{-0.75}$)	49.05	51.18	22.07 b	60.41 a	67.86 a	4.44	0.5813	< 0.0001	0.5688
Digestible energy intake (kcal per day kg $BW^{-0.75}$)	132.54	142.46	59.48 c	163.15 b	189.57 a	15.34	0.2247	< 0.0002	0.5510
Urinary gross energy (kcal kg $BW^{-0.75}$)	22.55	20.33	24.32	19.49	20.50	2.53	0.5527	0.5344	0.6654
Methane gross energy (kcal kg $BW^{-0.75}$)	6.90	6.72	6.50 ab	5.81 b	8.12 a	0.40	0.7662	0.0168	0.6652
Metabolizable energy intake (kcal per day kg $BW^{-0.75}$)	102.30	110.39	28.66 b	129.12 a	161.25 a	12.41	0.4625	< 0.0001	0.9258
Heat production (kcal per day kg $BW^{-0.75}$)	67.88	66.71	57.47 c	67.23 b	77.19 a	1.86	0.5632	< 0.0001	0.8296
Energy balance (kcal per day kg $BW^{-0.75}$)	35.13	43.68	-28.19 b	61.90 a	84.51 a	10.79	0.3886	< 0.0001	0.8809

[(1)]Means followed by different letters, in the same line, differ from each other by Tukey's test ($\alpha = 0.05$). [(2)]M-NRC, diet for maintenance of crude protein and total digestible nutrients; 85-NRC, diet meeting 85% of the recommendations of NRC; and 100-NRC, diet meeting100% of the recommendations of NRC.

Table 3. Results of mean, standard error of the mean (SEM), and p-values of the effects of sex, diet, and their interaction, as well as mean comparison of gross energy digestibility, metabolizability, and the metabolizable energy/digestible energy (ME/MD) ratio, obtained for noncastrated males (MS) and females (FS) of Brazilian Somali sheep fed diets based on the recommendations of National Research Council (NRC, 2007) for crude protein and total digestible nutrients[(1)].

Variable	Sex		Dietary treatment[(2)]			SEM	p-value		
	MS	FS	M-NRC	85-NRC	100-NRC		Sex	Diet	Sex × Diet
Gross energy digestibility (%)	72.89 a	73.43 a	72.97 A	72.77 A	73.74 A	0.51	0.5626	0.6504	0.548
Metabolizability	0.51 a	0.52 a	0.35 B	0.56 A	0.63 A	0.10	0.6706	< 0.0001	0.8551
ME/DE ratio	0.70 a	0.71 a	0.48 B	0.78 A	0.85 A	0.11	0.892	< 0.0001	0.7126

[(1)]Means followed by different uppercase letters comparing recommendations and lowercase letters comparing sexes differ from each other by Tukey's test ($\alpha = 0.05$). [(2)]M-NRC, diet for maintenance of crude protein and total digestible nutrients; 85-NRC, diet meeting 85% of the recommendations of NRC; and 100-NRC, diet meeting100% of the recommendations of NRC.

Tebbe, 2019). Furthermore, the high ME/DE ratio of those diets may have also been due to the low methane production based on dry matter and organic matter (Table 5). Although NRC (2007) considers 0.82 to be the ideal ratio, it is not recommended to adopt a fixed value since energy losses can be modified depending on animal species, consumption, or diet quality (Blaxter & Clapperton, 1965; Huston et al., 1986). In the present study, only the 100-NRC and 85-NRC diets had a ratio close to the ideal value according to NRC.

Oxygen consumption, CO_2 production, and respiratory quotient were influenced by diets ($p<0.05$). The highest O_2 consumption (liters per day) was recorded in 100-NRC, which did not differ statistically from 85-NRC. M-NRC showed the lowest O_2 consumption, but also did not differ significantly from 85-NRC. In addition, the 100-NRC and 85-NRC diets resulted in a higher CO_2 production than M-NRC. The values obtained for CO_2 production with 100-NRC and 85-NRC did not differ statistically in terms of liters per day, but did differ in terms of metabolic size. In this case, M-NRC differed significantly from the other diets in both measurements. Although the values obtained for metabolic size, O_2 consumption, CO_2 production, and respiratory quotient were similar, the diets differed statistically from each other, with the highest and lowest values found for 100-NRC and M-NRC, respectively (Table 4).

The lower O_2 consumption and CO_2 production observed under M-NRC are due to a lower dry matter intake (Alves, 2019). This finding is in alignment with that of Jentsch et al. (2009), who concluded that these variables are affected by the rate of feed intake, with lower O_2 consumption rates when animals are fed maintenance-level diets.

The respiratory quotient values were greater than 1.0 for 100-NRC and 85-NRC, meaning that the main energy source was carbohydrates (Table 1). The lower respiratory quotient observed for M-NRC reflected the negative energy balance of the animals subjected to this diet (Table 2), indicating that body energy was mobilized to meet energy demand.

Methane production (grams per day) was not significantly affected by the interaction between sex and diet or sex ($p>0.05$). However, diet influenced ($p<0.05$) all methane production variables. The highest methane production occurred under M-NRC, while 100-NRC and 85-NRC showed similar values. Meanwhile, methane production based on digestible and ingested NDF was lower in M-NRC, while 100-NRC and 85-NRC presented similar values (Table 5).

Methane production in ruminants is influenced by the quantity and digestibility of the consumed feed, as well as by the characteristics of the animals (Johnson & Johnson, 1995). This explains the low CH_4 (grams per day) production with M-NRC, which led to a low intake and dry matter digestibility (Alves, 2019). Furthermore, this diet showed a high proportion of roughage, which poses a challenge since a greater amount of fiber components provides more substrate for methanogenic bacteria, reducing the passage rate of digesta and, consequently, increasing CH_4 production (Ellis et al., 2009).

Table 4. Results of mean, standard error of the mean (SEM), and p-values of the effects of sex, diet, and their interaction, as well as mean comparison of gas exchanges and respiratory quotient, obtained for noncastrated males (MS) and females (FS) of Brazilian Somali sheep fed diets based on the recommendations of National Research Council (NRC, 2007) for crude protein and total digestive nutrients[(1)].

Variable	Sex		Dietary treatment[(2)]			SEM	p-value		
	MS	FS	M-NRC	85-NRC	100-NRC		Sex	Diet	Sex × Diet
Liters per day									
O_2 consumption	103.15 a	98.42 a	80.97 B	103.06 AB	118.33 A	3.24	0.5336	0.0026	0.9704
CO_2 production	117.53 a	114.28 a	79.84 B	119.82 A	148.06 A	4.84	0.7321	0.0001	0.7966
Liters per day kg $BW^{-0.75}$									
O_2 consumption	13.23 a	12.92 a	11.57 C	12.99 B	14.66 A	0.23	0.4292	< 0.0001	0.928
CO_2 production	14.94 a	14.96 a	11.41 C	15.13 B	18.30 A	0.44	0.9794	< 0.0001	0.5034
Respiratory quotient	1.12 a	1.15 a	0.99 C	1.16 B	1.25 A	0.02	0.2527	< 0.0001	0.2863

[(1)]Means followed by different uppercase letters comparing recommendations and lowercase letters comparing sexes differ from each other by Tukey's test ($\alpha = 0.05$). [(2)]M-NRC, diet for maintenance of crude protein and total digestible nutrients; 85-NRC, diet meeting 85% of the recommendations of NRC; and 100-NRC, diet meeting100% of the recommendations of NRC. BW, body weight.

When considering methane production based on dry matter and organic matter, the lower values found for 100-NRC and 85-NRC compared with M-NCR are due to the higher concentrate content in the diets, higher levels of rapidly fermentable carbohydrates, and greater digesta passage rate through the digestive tract (Johnson & Johnson, 1995). Van Kessel & Russel (1996) reported that a high soluble carbohydrate content leads to a greater reduction in rumen pH, increases fermentation rate, and inhibits the action of methanogenic microorganisms. Diets with high proportions of concentrate tend to produce less methane due to a high production of propionate, resulting in a better energy use efficiency (Whitelaw et al., 1984; Nussio et al., 2011).

IPCC (2006) estimates that sheep produce 8.0 kg of CH_4 per year. In the present study, the mean methane production was 1.51 kg per year, considering the mean daily production of 4.15 g per day for males and females. The mean emissions observed in the present study were lower than those of 5.41 kg CH_4 per year obtained by Costa (2021) for Santa Inês females under confinement and of 16.9 g per day found by Costa et al. (2020) for Santa Inês lambs managed on native Caatinga pasture, a vegetation characteristic of the Brazilian semiarid region. Therefore, it can be inferred that the confinement of ruminants, using high-concentrate diets, contributes positively to the reduction of methane emissions.

The values obtained for metabolizable energy intake, heat production, and retained energy in Brazilian

Table 5. Results of mean, standard error of the mean (SEM), and p-values of the effects of sex, diet, and their interaction, as well as mean comparison of daily methane (CH_4) production, obtained for noncastrated males (MS) and females (FS) of Brazilian Somali sheep fed diets based on the recommendations of National Research Council (NRC, 2007) for crude protein and total digestive nutrients[(1)].

Variable[(2)]	Sex		Dietary treatment[(3)]			SEM	p-value		
	MS	FS	M-NRC	85-NRC	100-NRC		Sex	Diet	Sex × Diet
CH_4 (g per day)	4.06 a	4.23 a	3.43 B	4.02 A	4.99 A	0.46	0.7460	0.0875	0.9587
CH_4 (g kg DMI^{-1})	17.22 a	19.77 a	33.36 A	10.68 B	11.46 B	4.11	0.3144	< 0.0001	0.3749
CH_4 (g kg DMD^{-1})	24.47 a	27.79 a	47.42 A	15.27 B	15.71 B	5.88	0.3533	< 0.0001	0.3407
CH_4 (g kg OMI^{-1})	17.57 a	18.76 a	29.19 A	12.86 B	12.43 B	2.93	0.3734	< 0.0001	0.7418
CH_4 (g kg OMD^{-1})	24.85 a	25.87 a	41.30 A	17.41 B	17.37 B	4.11	0.5663	< 0.0001	0.6642
CH_4 (g kg $NDFI^{-1}$)	46.26 a	41.45 a	28.71 B	48.39 A	54.46 A	2.75	0.1182	< 0.0001	0.1372
CH_4 (g kg $NDFD^{-1}$)	29.22 a	29.80 a	20.47 B	33.31 A	34.76 A	4.65	0.7939	< 0.0001	0.8818

[(1)]Means followed by different uppercase letters comparing recommendations and lowercase letters comparing sexes differ from each other by Tukey's test ($\alpha = 0.05$). [(2)]DMI, dry matter intake; DMD, dry matter digestibility; OMI, organic matter intake; OMD, organic matter digestibility; NDFI, neutral detergent fiber intake; and NDFD, neutral detergent fiber digestibility. [(3)]M-NRC, diet for maintenance of crude protein and total digestible nutrients; 85-NRC, diet meeting 85% of the recommendations of NRC; and 100-NRC, diet meeting100% of the recommendations of NRC.

Table 6. Metabolizable energy intake, heat production, and energy retention in noncastrated males (MS) and females (FS) of Brazilian Somali sheep fed diets based on the recommendations of National Research Council (NRC, 2007) for crude protein and total digestive nutrients.

Sex	Energy (kcal kg $BW^{-0.75}$ per day)	Dietary treatment[(1)]		
		M-NRC	85-NRC	100-NRC
Male	Metabolizable energy intake	27.51	123.01	156.37
	Heat production	57.81	67.22	78.61
	Retained energy	-29.06	55.81	78.63
Female	Metabolizable energy intake	29.80	135.23	166.14
	Heat production	57.12	67.24	75.76
	Retained energy	-27.33	67.99	90.38

[(1)]M-NRC, diet for maintenance of crude protein and total digestible nutrients; 85-NRC, diet meeting 85% of the recommendations of NRC; and 100-NRC, diet meeting100% of the recommendations of NRC. BW, body weight.

Somali sheep from different sex classes are shown in Table 6. The intercept of the equations (Figure 1) was significant ($p<0.05$). The nonlinear model parallelism test indicated no difference between sex classes for maintenance energy requirements according to the following formula used to estimate heat production:

$$HP = 53.98 (\pm 3.2) \times e^{0.0019(\pm 0.000392) \times MEI}$$

The NE_m for Brazilian Somali sheep was 53.98 kcal $kg^{-0.75}$ BW per day for the early growth phase, while ME_m was 60 kcal $kg^{-0.75}$ BW per day, with a k_m of 0.89.

The Brazilian Somali breed shows a great productive potential, as well as resilience to the semiarid climate. Its main characteristic is fat deposition in strategic body regions, such as the rump, which serves as a body energy reserve (Figueiredo, 2018). In the present work, the energy requirement value for Brazilian Somali sheep in the early growth phase was 53.98 kcal kg $BW^{-0.75}$, diverging from the values of 62 and 66 kcal kg $BW^{-0.75}$ recommended by NRC (2007) and CSIRO (2007), respectively. Climatic conditions are a factor contributing to this difference (CSIRO, 2007; Salah et al., 2014). Animals raised in tropical climates, especially in the semiarid region, for example, have a lower potential for muscle deposition, while depositing more fat than temperate-climate animals (Early et al., 2001). Therefore, the study of energy requirements for locally adapted animals is of utmost importance in setting reasonable nutrient goals and minimizing losses (Pereira et al., 2014).

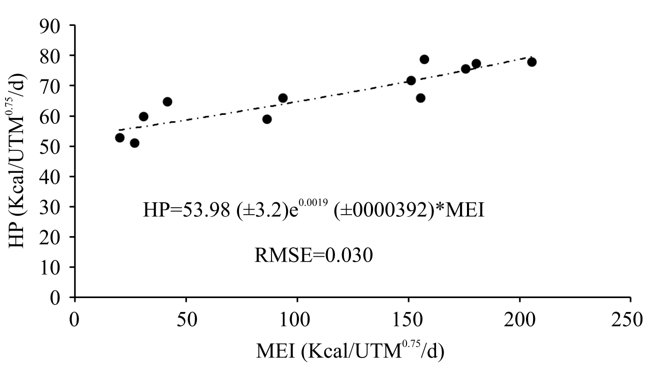

Figure 1. Relationship between heat production (HP) and metabolizable energy intake (MEI) in Brazilian Somali sheep.

Conclusions

1. The sex of the evaluated Brazilian Somali Sheep does not influence energy partitioning or methane production.
2. The diet using 85% of the recommendations of National Resource Council (NRC) for crude protein and total digestible nutrients can be offered without reducing energy efficiency.
3. Diets using 100 and 85% of NRC recommendations for crude protein and total digestible nutrients lead to a reduction in daily methane production.
4. The net energy requirements for Brazilian Somali sheep in the early growth phase does not differ between sexes.

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Data availability statement

The data supporting the findings of this study are available in the article. Should any raw data be needed, they will be provided by the corresponding author upon reasonable request.

Declaration of use of AI technologies

No generative artificial intelligence (AI) was used in this study.

Conflict of interest statement

The authors declare no conflicts of interest.

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