Meat Science 194 (2022) 108959

Contents lists available at ScienceDirect

Meat Science

journal homepage: www.elsevier.com/locate/meatsci

Characteristics of growth, carcass and meat quality of sheep with different feed efficiency phenotypes

Danielle Nunes Gurgeira [a], Charleni Crisóstomo [a], Luiza Vage Coelho Sartori [a], Claudia Cristina Paro de Paz [b], Gustavo Delmilho [a], Alfonso Juventino Chay-Canul [c], Héctor Javier Narvaez Bedoya [d], Wilder Hernando Ortiz Vega [e], Mauro Sartori Bueno [a], Ricardo Lopes Dias da Costa [a,*]

[a] Instituto de Zootecnia, Rua Heitor Penteado, 56, Nova Odessa, SP 13380-011, Brazil
[b] Instituto de Zootecnia, Rodovia Carlos Tonani, km 94, Sertãozinho, SP 14160-900, Brazil
[c] Universidad Juárez Autónoma de Tabasco, Carretera Villahermosa-Teapa, km 25, R/A La Huasteca, Centro, Tabasco, C.P. 86280, Mexico
[d] Universidad de Santander, Calle70, n 55-210, Bucaramanga, Santander, Colômbia
[e] Centro Universitário UNINTA, Rua. Antônio Rodrigues Magalhães, 359 - Dom Expedito, Sobral, CE 62050-100, Brazil

ARTICLE INFO

Keywords:
Automatic feeder
Feedlot
Genetic selection
Lamb meat
Residual feed intake

ABSTRACT

The objective was to evaluate the performance, carcass and meat quality of 40 lambs classified by RFI (residual feed intake) and RIG (residual intake and gain). Dry matter intake (DMI) was recorded to calculate the RFI and RIG, classified as efficient, moderately or inefficient. After the confinement period, they were slaughtered and the carcass and meat quality were determined. The efficient animals had DMI scores of 0.700 RFI and 0.400 kg/d RIG, lower than the inefficient ones with similar weight gain. The RFI efficient animals showed greater shear force, without effect in the RIG classification. In general, the variables analyzed were not influenced by RFI or RIG. Efficiency measures do not affect the carcass and meat quality of sheep, but they do have the advantage of identifying animals with lower feed consumption, making the system more efficient. However, as the dataset is limited to fully assess the effects, this manuscript can be used as preliminary results for future studies.

1. Introduction

Keeping sheep herds that are more efficient in the use of food will lower the corresponding feed costs. The ability to transform ingested food into meat, milk or wool is defined as feed efficiency. Determination of this important parameter allows selection of more productive and less polluting animals, reducing the environmental impact and increasing the profitability of livestock systems (Soleimani & Gilbert, 2020).

The identification and selection of efficient animals can be done by ascertaining measures of feed efficiency (FE), nutrient digestibility, eating behavior, hormonal profiling and blood biochemistry (Bourgon, Diel de Amorim, Miller, & Montanholi, 2017; Karisa et al., 2014; Zhang et al., 2017). Regarding FE measurements, Koch, Swiger, Chambers, and Gregory (1963) proposed the residual feed intake (RFI) metric, which considers more efficient animals to be those that consume less feed than expected for the population based on their size and growth rate.

However, some more efficient animals can show low weight gain (WG), reducing the acceptance of breeders. In light of this, in the case of cattle Berry and Crowley (2012) proposed another measure of feed efficiency called residual intake and gain (RIG). This is an independent parameter of live weight, negatively correlated with intake and positively correlated with WG, in which the most efficient animals are those with lower dry matter intake (DMI) and higher WG in relation to the averages of the population studied.

In cattle, metabolic discrepancies between efficient and inefficient animals can be important factors in the productive performance of animals. Non-carcass components have been reported to contribute 5% as biological mechanisms that contribute to the variation in feeding efficiency (Richardson, Herd, Archer, & Arthur, 2004). Size differences in organs such as the liver and pancreas are found among these categories of animals (Montanholi et al., 2017). The size and functionality of the liver and organs of the gastrointestinal tract are associated with metabolic cost. There is a relationship between feed intake and energy used to digest it, whereby higher intake is associated with greater energy

* Corresponding author.
E-mail address: rldcosta@sp.gov.br (R.L.D. da Costa).

https://doi.org/10.1016/j.meatsci.2022.108959
Received 24 January 2022; Received in revised form 25 August 2022; Accepted 26 August 2022
Available online 5 September 2022

expenditure, due to an increase in the size of the digestive organs and the energy expended within the tissues of these organs (Herd & Arthur, 2009). In this respect Zhang et al. (2017) reported that low-RFI lambs had smaller size of liver, lungs, kidneys and total stomach weight, and greater length of the duodenum and ileum than high-RFI lambs. In beef bulls with higher feed efficiency, undesirable effects such as decreased sperm motility and viability and scrotal circumference have been reported (Awda et al., 2013).

Regarding carcass traits, genotypic and phenotypic variations in RFI were not associated with any harmful effect on the carcass quality of cattle (Gomes et al., 2012; Zorzi et al., 2013) or lambs (Zhang et al., 2017). Despite these findings, studies involving the management of electronic troughs in the calculation of feed efficiency and its associations with carcass characteristics are scarce for sheep, despite the growing international interest in research on the feeding efficiency of ovines (Amarilho-Silveira et al., 2022; Arce-Recinos et al., 2022; Azizi et al., 2021; Freitas et al., 2020; Freitas, Bartholazzi Junior, Quirino, & Costa, 2021; Mupfiga et al., 2022). Although the RFI and RIG do not measure the adult size of animals and bring economic advantages to the production system, it is necessary to identify possible antagonistic correlations between these efficiency measures and characteristics of economic interest, such as carcass characteristics and meat quality, which can affect acceptance in the consumer market. Therefore, the objective of this study was to evaluate the carcass characteristics and meat quality of sheep classified according to residual feed intake and residual intake and gain, using an automated feeding system.

2. Material and methods

The experiment was approved by the Animal Use Ethics Committee of the Animal Science Institute/APTA – CEUA/IZ, under technical opinion no. 280/19.

2.1. Animals, diet and facilities

Forty uncastrated male Santa Ines lambs, born in the same lambing season, with initial ages of 187 ± 30 days and average initial weight of 44.5 ± 4.1 kg, were evaluated. The animals were collectively confined in a single pen equipped with nine automatic feeder stations and two automatic drinking troughs (Intergado Efficiency®, Betim, MG, Brazil). The lambs were fed a total diet during the experimental period (RC Dieta Total Confinamento®, Coopermota, Cândido Mota, SP, Brazil) according to the nutritional requirements recommended by the National Research Council (NRC, 2007) for lambs in the finishing phase and under a confinement system (Supplementary Table S1). Water and feed were provided ad libitum. The diet consisted of Tifton 85 hay, ground corn, soybean meal and limestone, with a roughage:concentrate ratio of 10:90, in the chopped form.

The animals had already participated in an efficiency trial that lasted 80 days prior to this experiment, and therefore were adapted to the facilities and diet. Consumption and weight data were recorded individually during 61 days of confinement by the electronic system, using an animal identification chip (each lamb was individually identified at the electronic trough by an electronic chip hanging from the collar). These data were used for further estimation of the RFI and RIG. Based on this information, the animals were categorized into three classes for the two efficiency measures, as follows: residual feed intake (RFI+, RFI±, RFI-, denoting highly efficient, moderately efficient or inefficient, respectively), and residual intake and gain (RIG+, RIG± and RIG-, denoting highly efficient, moderately efficient and inefficient, respectively).

2.2. Measures of performance and feed efficiency

Measures/equations accepted worldwide for the evaluation of performance and feed efficiency are detailed in Table 1.

Table 1
Equations used to calculate measures of performance and feed efficiency index.

	Equations
Measures of Performance	
TWG	FLW – ILW
ADG	TWG/61
DMIav	∑DMI (D0, D1, D2, …, D61)/61
$LW^{0.75av}$	$[(ILW + FLW)/2]^{0,75}$
Index	
FE	ADG/DMI
FC	DMI/ADG
RWG	ADGobs - ADGexp
RGR	100 × (logFLW - logIFW)/61
KR	$ADG/LW^{0.75av}$
RFI	DMIobs - DMIexp
RG	ADGobs - ADGexp
RIG	-1 × RFI + RG

TWG = total weight gain (kg), FLW = final live weight (kg), ILW = initial live weight (kg), ADG = average daily gain (kg/day), DMIav = average dry matter intake (kg/day), FE = feed efficiency (kg/kg), DMI = dry matter intake (kg/day), FC = feed conversion (kg/kg), RWG = residual weight gain (kg), ADGobs = average daily gain observed (kg/day), ADGexp = expected mean daily gain (kg/day), $LW^{0.75av}$ = metabolic mean live weight (kg), RGR = relative growth rate, KR = Kleiber rate, RFI = residual feed intake (kg/day), DMIobs = observed dry matter intake (kg/day), DMIexp = expected dry matter intake (kg/day), RG = residual gain (kg), RIG = residual intake and gain (kg/kg).

2.3. Zoometric indices

The morphometric measurements of the animals were performed at the beginning and end of the experimental period, using a measuring tape and an adapted ruler. The lambs were kept in an upright position on a concrete floor with no slope during measurements. From the relationships between the morphometric measures, the zoometric indices were calculated (Table 2).

2.4. Slaughter and carcass characteristics

For slaughter, the animals were stunned following the rules on Industrial and Sanitary Inspection of Products of Animal Origin of Brazil (Regulation of Industrial and Sanitary Inspection of Products of Animal

Table 2
Morphometric measurements and equations used to calculate zoometric index.

Morphometric measurements	Localization
Body length (BL)	obtained from the cranial point of the humerus greater tuberosity to the ischial tuberosity caudal point
Withers height (WH)	measure from withers to the floor
Rump height (RH)	measure from sacrum anterior portion to the floor
Thoracic perimeter (TP)	corresponded to the outer circumferenceof the chest cavity, immediately caudal to the scapula via the sternum and the processes spinal thoracic vertebrae
Abdominal circumference (AC)	measure that involves the abdomen at its largest circumference
Abdomen-floor (AF)	distance from the most distal point of the abdomen to the floor
Testicular circumference (TC)	testicle circumference at median height
Zoometric index	EQUATIONS
Body capacity 1 (BC1)	weight/BL
Body capacity 2 (BC2)	weight/TP
Body index (BI)	(BL/TP)*100
Anamorphosis index (ANAMI)	$TP/(TP)^2$
Compactness index (COMI)	(weight/WH)*100
Proportionality index body (PROPI)	(COMI/BI)*100
Lateral body index (LATI)	(WH/BL)*100

Origin (RIISPOA, 2017)). For this purpose, 20 animals were chosen using the classification into three categories for RFI; (efficient = 7; moderately efficient = 8; inefficient = 5). The animals for slaughter were randomly chosen, within the same class of residual feed intake (RFI), corresponding to 53.8%, 47% and 50%, respectively, for the most efficient, moderate or inefficient animals. In the RIG classification, 5 animals were classified as efficient (RIG+), 11 as moderate (RIG±) and 4 as inefficient (RIG-).

The slaughter took place at the end of the test, in a single batch (all in the morning of the same day). Because the ages of the animals were very close and the slaughter body weight between the classes did not differ significantly (61.93 ± 2.34 kg, 58.50 ± 2.19 kg and 60.70 ± 2.76 kg, p = 0.564, respectively, for the three classes), these characteristics were tested as covariates, but since they were not significant, they were removed from the model.

At end of the trial, the animals were fasted from solid food for 16 h, weighed (slaughter body weight - SBW) and slaughtered. After the animals were slaughtered, the digesta were totally removed from the gastrointestinal tract to obtain the empty body weight (EBW), and after removing and weighing the non-carcass components, the carcasses were weighed to obtain the hot carcass weight (HCW). After weighing the hot carcasses, they were placed in a cold chamber at 4 °C for 24 h. Then the cold carcass weight (CCW) was determined, and the HCW and CCW were used to calculate the following carcass-related parameters: hot carcass yield (HCY) = (HCW/SBW) × 100; cold carcass yield (CCY) = (CCW/SBW) × 100; cooling loss (CL) = [(HCW - CCW) × 100]/HCW; and live biological yield (LBY) = (HCW/EBW) × 100 (Pérez & Carvalho, 2007). Separately, the reproductive tract with urinary bladder, renal pelvic fat, respiratory tract, full and empty gastrointestinal tract, heart, head, feet, skin, kidneys, spleen and liver were weighed and, portions of the intestine (duodenum and jejunum, ileum, cecum, colon and rectum) were measured using a tape measure. After skinning and evisceration, the carcasses were placed in a cold chamber at 4 °C for 24 h. The temperature and pH were measured in the semimembranosus (SM) muscle, at 0 and 24 h after slaughter, using a Q400HM digital potentiometer (QUIMIS®, Diadema, São Paulo, Brazil). The SM was used to measure the pH value, sinse it represents the entire carcass and does not compromise the integrity of the *Longissimus lumborum* (LL) portion. pH was measured using meters with temperature compensation (Hanna HI99163 water prof meat pHmeter) supplied with electrodes with internal temperature sensor and stainless steel blade, with pH resolution of 0.01, pH accuracy ±0.02 and automatic calibration with two-point buffer set standard for pH 4.01, 7.01.

The LL muscle was removed from the left half of the carcass and separated from bones. The LL section used comprised the portion between the penultimate vertebra of the thoracic portion to the end of the lumbar portion. It was then divided into two subsamples, vacuum packed and frozen at −20 °C for subsequent chemical and physical analyses.

Conformation and finishing parameters (fat level) were determined by visual evaluation of the carcass, according to Cezar and Sousa (2018). Conformation was determined by assigning a score from 1 to 5, according to the arrangement of muscle and adipose tissues in relation to the skeleton supporting them (on a scale of 1 = very poor to 5 = excellent). The subjective evaluation of carcass fat coverage was performed using a score ranging from 1.0 to 5.0 (1.0 = low-finish carcass and 5.0 = high-finish carcass).

2.5. Carcass measurements

To obtain the morphometric measurements of the carcasses and half carcasses, a tape measure was used for circular measurements and a ruler for linear measurements. After these measurements, each carcass was sectioned longitudinally and the left hemicarcass was weighed and the commercial cuts (neck, palette, chest-flank, rib, loin, and thigh) were weighed to determine the individual yields (in percentage) in relation to the reconstituted hemicarcass weight.

The measures were: external carcass length (ECL) = distance between the base of the neck and the base of the tail; croup width (CW) = distance between the two trochanters of the femurs; chest width (ChW) = distance between the ribs; croup perimeter (CPer) = perimeter around the croup at the height of the trochanters; internal carcass length (ICL) = maximum distance between the anterior edge of the ischiopubic symphysis and the anterior edge of the first rib; leg length (LLg) = distance between the anterior edge of the pelvic symphysis and the inner edge of the tarsometatarsal articular surface; leg perimeter (LP); leg depth (LD) = greatest distance between proximal and distal edge of the leg, measured with an adapted ruler and measuring tape; and chest depth (CD) = distance between the back and the sternum, i.e., maximum distance between the region of the crosses and the sternal crest (Cezar & Sousa, 2018; Neto, da Cruz, Faria, Souza, & Nunes, 2016).

The loin eye area of LL muscle was calculated at the height of the penultimate thoracic vertebra, by the checkered transparent template, 1 cm^2 $cell^{-1}$, and the thickness of subcutaneous fat (TSF) was measured with a caliper (Cezar & Sousa, 2018).

2.6. Color

Muscle color by the CIElab colorimetric system was determined using a colorimeter (Minolta model CM-600d, Konica Minolta, USA). The system used considers the following coordinates: luminosity, L* (reflectance or transmittance), a* (red ratio) and b* (yellow ratio). The standard observer, illuminant and aperture used were: degree of observer- 2°; light source (illuminant)- D65 (daylight at noon) and size of measuring port- 8 mm. Three readings were taken of each sample and the average of the results was obtained.

2.7. Cooking losses

LL steaks, approximately 2.5 cm thick, were taken from the region between the penultimate and last thoracic vertebrae, on the left side of the carcass and frozen. At the time of analysis, the samples were placed in a refrigerator for 24 h for slow thawing and then removed and allowed to reach room temperature for later weighing. Thawed samples were weighed, placed on disposable aluminum trays and weighed. Next, they were individually roasted in an electric oven until reaching an internal temperature of 70 °C, removed from the oven, left at room temperature, and weighed again. The liquid was drained and the sample was weighed again. Cooking losses (post-thawing and post-cooking) and drainage losses were calculated by the difference between these weights. Evaporation loss was calculated as the difference between the weights of the raw sample and the weight of the roasted sample without draining.

2.8. Shear force

Shear force was applied to the roasted LL steaks after being refrigerated for 24 h. Five cylinders parallel to the muscle fibers were removed with the aid of a cylindrical mold from each sample of the roasted and refrigerated LL steaks and the shear force was measured with a texturometer (TA-XT 2i), coupled with a Warner Bratzler blade (1 mm thick). The equipment was calibrated with a standard weight of 5 kg. The device's descent rate was 200 mm/min (AMSA, 1995). The final value was considered to be the mean of the 5 readings per sample, expressed in Newtons (N).

2.9. Physical-chemical analysis of meat

The samples of LL steaks taken from the right side of the carcass and frozen were ground and placed in thin layers in plastic Petri dishes with a diameter of 9 cm, weighed and placed in a freeze-dryer for cold drying until reaching constant weight. After being removed from the lyophilizer and reaching room temperature, they were weighed again and crushed with dry ice to reduce the particle size for chemical analysis. The lyophilized dry samples were sent to the laboratory for analysis of their proximate composition. Protein analysis was performed using the Kjeldahl method, in which total nitrogen was multiplied by a conversion factor of 6.25 (AOAC 981.10). The ether extract was determined by the Soxhlet method (AOAC 960.3). Moisture was determined by gravimetry using an oven at 105 °C (AOAC 950.46B), and ash using a muffle furnace with average temperature of 600 °C (AOAC 950.46), following the recommendations of the Association of Official Analytical Chemists (AOAC, 2012). Carbohydrates were calculated by difference, where all values obtained from the analyses performed were subtracted from 100 (Van Soest, Robertson, & Lewis, 1991).

2.10. Statistical analysis

All statistical analyses were performed using the SAS statistical software (SAS, Inst., Inc., Cary, NC, USA). A completely randomized experimental design was used. Initially, the homogeneity of variances and the frequency distribution of residuals were tested using histograms and tests in PROC UNIVARIATE.

The average daily gain (ADG) of each animal was estimated by the linear regression coefficient of weights as a function of days under test (DUT): $yi = \alpha + \beta^*DUTi + \varepsilon i$, where yi = animal weight at the ith observation; α = intercept of the regression equation representing the initial weight; β = linear regression coefficient representing the ADG; DUTi = test days at the ith observation; and εi = random error associated with each observation.

The mean metabolic live weight ($LW^{0.75av}$) was calculated as: $LW^{0.75} = [\alpha + \beta^*(\text{test duration})/2]0.75$, where: α and β were as previously described. Dry matter intake (DMI) was obtained as the mean of valid days (average daily DMI) during the test phase (1–61 days).

The RFI was estimated according to the following multiple regression model: $DMI = \beta0 + \beta1^*ADG + \beta2^*LW^{0.75} + \text{error}$, where β0 is the regression intercept, β1 is the average intake regression coefficient over ADG, β2 is the DMI regression coefficient over $LW^{0.75}$, and the error is RFI, which is the difference between DMIobs and the DMIexp. The animals were classified into three classes only for RFI: efficient (RFI < mean - 0.5 standard deviation; RFI-), intermediate (mean - 0.5 standard deviation < RFI < mean + 0.5 standard deviation; RFI±) and inefficient (RFI > mean + 0.5 standard deviation; RFI+), based on the respective RFI value. Likewise, they were classified into three classes for RIG: efficient (RIG > mean + 0.5 standard deviation; RIG+), intermediate (mean - 0.5 standard deviation < RIG < mean + 0.5 standard deviation; RIG±), and inefficient (RIG < mean – 0.5 standard deviation; RIG-), based on the respective RIG value.

Analysis of variance (ANOVA) was performed for the feed efficiency characteristics, carcass characteristics, meat quality and zoometric indices, by PROC GLM, with adjustment in the model of the fixed effect of RFI classes (efficient, intermediate and inefficient) or RIG classes (inefficient, intermediate and efficient). The fixed effects of RFI and RIG classes of the studied characteristics were compared using the Tukey test, with the PROC GLM LSmeans command.

3. Results

Among the animals evaluated by RFI, 13 were classified as efficient (RFI-), 17 moderately efficient (RFI±) and 10 inefficient (RFI+). In the RIG classification, 10 lambs were in the efficient group (RIG+), 19 were moderate group (RIG±) and 11 were inefficient (RIG-) (Table 3).

The characteristics DMI, DMI in relation to live weight (DMI%LW - %), FE and FC were significantly different ($P < 0.05$) between categories for both RFI and RIG. RFI- animals consumed 0.7 kg/day less than RFI+ animals ($P < 0.01$) and had 1.3% less DMI%LW ($P < 0.01$), while for FE, they produced 50 g more per kilogram of DM ingested ($P < 0.01$), and consumed 3.17 kg of DM less to produce 1 kg of live weight ($P < 0.01$). The results for RIG followed the same pattern as those presented for RFI (Table 3). The variables ADG, TWG, KR, RGR and $LW^{0.75}$ did not differ between the efficiency groups, both for RFI and RIG ($P > 0.05$).

The zoometric indices studied in this work were not influenced ($P > 0.05$) by the RFI and RIG classifications (Table 4). In all groups, the two body capacity indices (BCI1 and BCI2) had mean values of 0.7 and 0.58 respectively (Table 4).

The carcass characteristics of the lambs did not differ ($P > 0.05$) in relation to the RFI and RIG classifications, as shown in Table 5. Mean pre-fasting weight of animals, fasting live weight, hot carcass weight, cold carcass weight and half carcass weight presented values of 62.8 Kg; 60.4 kg; 31.45 kg; 30.81 kg and 15.7 kg, respectively. The commercial cuts and their yields were similar ($P > 0.05$) between inefficient (RFI+, RIG-), moderately efficient (RFI±, RIG±) and efficient animals for RFI (RFI-) and RIG (RIG+) (Table 5). Non-carcass components were not affected by RFI and RIG ($P > 0.05$) (Table 6).

The qualitative characteristics of the meat were not influenced by the efficiency measures, with the exception of the shear force ($P = 0.015$). Animals classified as efficient by RFI (RFI-) had higher shear force compared to less efficient animals. This difference was not observed for the RIG classification ($P = 0.063$) (Table 7).

The pH values were not influenced by RFI and RIG ($P > 0.05$), with a mean pH 0 value of 6.1 and pH 24 of 5.6 (Table 5). Regarding meat color, no differences were found ($P > 0.05$) between the RFI and RIG classes for any of the L*, a* and b* ranges (Table 5). Also, no differences

Table 3
Averages of performance characteristics of lambs classified by residual feed intake (RFI) and residual intake and gain (RIG).

	RFI				RIG			
	EFI (RFI-)	MED (RFI±)	INEF (RFI+)	*P*-value	EFI (RIG+)	MED (RIG±)	INEF (RIG-)	*P*-value
	n = 13	n = 17	n = 10		n = 10	n = 19	n = 11	
RFI	-0.439^a ± 0.056	-0.039^b ± 0.049	0.637^c ± 0.064		.	.	.	
RIG	.	.	.		0.967^c ± 0.124	0.086^b ± 0.109	-1.404^a ± 0.142	
DMI	1.38^b ± 0.08	1.61^b ± 0.07	2.08^a ± 0.09	<0.001	1.48^b ± 0.11	1.61^{ab} ± 0.08	1.88^a ± 0.11	0.045
DMI%	2.63^c ± 0.13	3.07^b ± 0.11	3.93^a ± 0.15	<0.001	2.78^b ± 0.19	3.05^b ± 0.14	3.63^a ± 0.19	0.009
ADG	0.23 ± 0.02	0.23 ± 0.01	0.24 ± 0.02	0.959	0.24 ± 0.02	0.23 ± 0.01	0.23 ± 0.02	0.924
TWG	13.71 ± 0.98	13.64 ± 0.86	13.71 ± 1.12	0.998	14.98 ± 1.09	13.48 ± 0.79	12.85 ± 1.04	0.354
FE	0.17^a ± 0.01	0.14^b ± 0.01	0.11^b ± 0.01	<0.001	0.17^a ± 0.01	0.14^{ab} ± 0.01	0.11^b ± 0.01	0.003
FC	6.29^b ± 0.50	7.70^{ab} ± 0.44	9.46^a ± 0.58	0.001	6.37^b ± 0.61	7.56^{ab} ± 0.45	9.10^a ± 0.59	0.010
KR	0.004 ± 0.0004	0.004 ± 0.0004	0.005 ± 0.0005	0.435	0.005 ± 0.0005	0.004 ± 0.0004	0.005 ± 0.0005	0.602
RGR	0.19 ± 0.01	0.19 ± 0.01	0.19 ± 0.01	0.994	0.21 ± 0.01	0.19 ± 0.01	0.18 ± 0.01	0.372
$LW^{0.75av}$	19.10 ± 0.37	19.12 ± 0.32	19.33 ± 0.42	0.902	19.35 ± 0.42	19.17 ± 0.31	18.98 ± 0.40	0.823

Means followed by different letters in the lines are statistically different by the Tukey test with a probability level of 5%. n = number of animals classified as efficient, medium or less efficient, out of a total of 40 animals to estimate the RFI and RIG. EFI = efficient, MED = medium, INEF = inefficient, DMI = dry matter intake (Kg/day), DMI% = dry matter intake in relation to live weight (%), ADG = average daily gain (kg/day), TWG = total weight gain (kg), FE = feed efficiency, FC = feed conversion, KR = Kleiber rate, RGR = relative growth rate, $LW^{0.75av}$ = metabolic mean live weight.

Table 4
Zoometric indexes of lambs classified by residual feed intake (RFI) and residual intake and gain (RIG).

	RFI				RIG			
	EFI (RFI-)	MED (RFI±)	INEF (RFI+)	*P*- Value	EFI (RIG+)	MED (RIG±)	INEF (RIG-)	*P*-Value
	n = 13	n = 17	n = 10		n = 10	n = 19	n = 11	
BCI1	0.69 ± 0.02	0.69 ± 0.01	0.71 ± 0.02	0.545	0.70 ± 0.02	0.69 ± 0.01	0.71 ± 0.02	0.822
BCI2	0.58 ± 0.01	0.58 ± 0.01	0.60 ± 0.01	0.516	0.58 ± 0.01	0.59 ± 0.01	0.58 ± 0.01	0.925
BoI	84.04 ± 1.00	83.73 ± 0.87	83.62 ± 1.14	0.955	83.76 ± 1.09	84.66 ± 0.79	82.36 ± 1.04	0.228
ANAMI	88.62 ± 0.88	88.32 ± 0.77	87.80 ± 1.01	0.830	88.50 ± 1.01	88.21 ± 0.73	88.23 ± 0.96	0.971
COMI	78.61 ± 1.79	77.90 ± 1.57	78.13 ± 2.04	0.955	78.59 ± 2.04	78.30 ± 1.48	77.62 ± 1.95	0.937
BoPROPI	94.09 ± 2.64	93.17 ± 2.31	93.91 ± 3.01	0.961	94.42 ± 3.00	92.73 ± 2.17	94.55 ± 2.86	0.843
BoCOLI	88.05 ± 1.11	89.21 ± 0.97	91.72 ± 1.26	0.099	89.00 ± 1.29	88.69 ± 0.94	91.20 ± 1.23	0.259

Means followed by different letters in the lines are statistically different by the Tukey test with a probability level of 5%. n = number of animals classified as efficient, medium or less efficient, out of a total of 40 animals to estimate the RFI and RIG. EFI = efficient, MED = medium, INEF = inefficient, BCI1 = body capacity indice 1, BCI2 = body capacity index 2, BoI = body index, ANAMI = anamorphosis index, COMI = compactness index, BoPROPI = body proportionality index, BoCOLI = lateral body index.

Table 5
Means of morphometric measurements and carcass characteristics and commercial cuts of lambs classified by residual feed intake (RFI) and residual intake and gain (RIG).

	RFI				RIG			
	EFI (RFI-)	MED (RFI±)	INEF (RFI+)	*P*- value	EFI (RIG+)	MED (RIG±)	INEF (RIG-)	*P*- value
	n = 7	n = 8	n = 5		n = 5	n = 11	n = 4	
Carcass measurements (cm)								
FT***	5.81 ± 0.60	4.64 ± 0.56	6.48 ± 0.71	0.132	5.20 ± 0.79	5.57 ± 0.53	5.73 ± 0.89	0.894
REA**	19.93 ± 0.99	19.20 ± 0.93	18.82 ± 1.17	0.753	19.84 ± 1.16	18.85 ± 0.78	20.16 ± 1.30	0.623
ECL	73.57 ± 3.45	74.13 ± 3.22	80.25 ± 4.56	0.474	69.80 ± 3.55	79.36 ± 2.39	69.00 ± 4.58	0.052
RW	20.93 ± 0.53	20.43 ± 0.49	20.63 ± 0.70	0.786	20.04 ± 0.60	20.75 ± 0.40	21.33 ± 0.77	0.414
ChW	26.76 ± 0.90	26.58 ± 0.84	27.30 ± 1.19	0.882	27.40 ± 1.04	26.350.70	27.40 ± 1.34	0.634
RP	70.54 ± 1.24	70.26 ± 1.16	73.63 ± 1.64	0.243	70.12 ± 1.54	71.02 ± 1.04	72.87 ± 1.99	0.563
ICL	68.87 ± 1.51	68.63 ± 1.41	65.40 ± 1.79	0.293	69.40 ± 1.87	67.46 ± 1.26	67.25 ± 2.09	0.658
LLg	44.81 ± 1.25	43.63 ± 1.17	47.80 ± 1.48	0.114	44.92 ± 1.68	45.37 ± 1.13	44.50 ± 1.88	0.918
LP	46.94 ± 0.65	47.38 ± 0.61	47.80 ± 0.77	0.702	48.20 ± 0.74	46.87 ± 0.50	47.50 ± 0.83	0.349
LD	11.57 ± 0.37	11.63 ± 0.34	11.54 ± 0.43	0.987	11.62 ± 0.41	11.38 ± 0.28	12.10 ± 0.46	0.426
ChP	32.64 ± 0.65	32.36 ± 0.61	32.80 ± 0.77	0.897	32.46 ± 0.86	32.74 ± 0.52	32.46 ± 0.77	0.878
Score								
CFCS	2.79 ± 0.19	2.63 ± 0.18	2.90 ± 0.23	0.636	2.70 ± 0.23	2.69 ± 0.15	3.00 ± 0.26	0.559
CCF	2.64 ± 0.16	2.69 ± 0.15	2.70 ± 0.19	0.969	2.60 ± 0.19	2.64 ± 0.13	2.88 ± 0.21	0.564
Weight (Kg)								
SBW	61.93 ± 2.34	58.50 ± 2.19	60.70 ± 2.76	0.564	63.30 ± 2.71	59.64 ± 1.83	58.13 ± 3.03	0.412
HCW	32.04 ± 1.18	30.46 ± 1.10	32.06 ± 1.39	0.548	32.42 ± 1.41	31.33 ± 0.95	30.40 ± 1.57	0.633
CCW	31.41 ± 1.14	29.83 ± 1.07	31.44 ± 1.35	0.521	31.70 ± 1.36	30.74 ± 0.92	29.78 ± 1.53	0.648
1/2CW	16.21 ± 0.74	15.33 ± 0.69	15.66 ± 0.87	0.682	16.34 ± 0.86	15.75 ± 0.58	14.85 ± 0.96	0.523
EBW	54.31 ± 1.99	51.71 ± 1.86	54.27 ± 2.35	0.570	55.62 ± 2.33	52.78 ± 1.57	51.63 ± 2.61	0.485
HCY*	51.90 ± 0.77	51.40 ± 0.72	52.41 ± 0.91	0.682	51.34 ± 0.92	52.02 ± 0.62	51.89 ± 1.02	0.828
CCY*	50.81 ± 0.94	51.03 ± 0.88	51.87 ± 1.11	0.754	50.06 ± 1.08	51.61 ± 0.73	51.31 ± 1.21	0.506
CY*	51.82 ± 0.95	52.11 ± 0.89	52.89 ± 1.13	0.763	51.20 ± 1.11	52.59 ± 0.75	52.38 ± 1.24	0.588
LD*	1.94 ± 0.18	2.09 ± 0.16	1.93 ± 0.21	0.772	2.23 ± 0.20	1.87 ± 0.13	2.05 ± 0.22	0.315
Leg	4.42 ± 0.17	4.13 ± 0.16	4.49 ± 0.20	0.285	4.52 ± 0.20	4.25 ± 0.14	4.27 ± 0.23	0.529
Loin	1.22 ± 0.14	1.17 ± 0.13	1.33 ± 0.17	0.748	1.29 ± 0.17	1.23 ± 0.11	1.13 ± 0.19	0.817
Rack	1.93 ± 0.11	1.85 ± 0.10	1.79 ± 0.13	0.697	2.03 ± 0.11	1.89 ± 0.08	1.59 ± 0.13	0.051
Breast	2.55 ± 0.19	2.11 ± 0.18	2.08 ± 0.23	0.189	2.50 ± 0.23	2.26 ± 0.16	1.94 ± 0.26	0.292
Neck	1.37 ± 0.11	1.27 ± 0.10	1.18 ± 0.13	0.532	1.44 ± 0.12	1.27 ± 0.08	1.11 ± 0.14	0.220
Shoulder	2.43 ± 0.11	2.49 ± 0.10	2.60 ± 0.13	0.583	2.65 ± 0.13	2.47 ± 0.08	2.39 ± 0.14	0.340
Chest	1.23 ± 0.09	1.16 ± 0.09	1.29 ± 0.11	0.654	1.21 ± 0.11	1.28 ± 0.07	1.04 ± 0.12	0.248

Means followed by different letters in the lines are statistically different by the Tukey test with a probability level of 5%. n = number of animals classified as efficient, medium or less efficient, out of a total of 20 animals slaughtered out of a total of 40 animals used to estimate the RFI and RIG. EFI = efficient, MED = medium, INEF = inefficient, FT = fat thickness, REA = rib eye area, ECL = external carcass length, RW = rump width, ChW = chest width, RP = rump perimeter, ICL = internal carcass length, LLg = leg length, LP = leg perimeter, LD = leg depth, ChP = chest perimeter, CFCS = carcass fat cover score, CCF = carcass conformation score, SBW = slaughter body weight, HCW = hot carcass weight, CCW = cold carcass weight, 1/2CW = half carcass weight, EBW = empty body weight, *** = measured in millimeters, ** = area in cm2, * = measured in percentage, HCY = hot carcass yield, CCY = cold carcass yield, CY = carcass yield.

($P > 0.05$) were detected in the proximate composition of the LL muscle between the RFI and RIG classes (Table 6).

No physical-chemical analysis (dry matter, crude protein, ether extract and mineral matter) of the *Longissimus lumborum* muscle were different between the RFI and RIG characteristics ($P > 0.05$, Table 8).

4. Discussion

The premise that the production of meat from ruminants is associated with a high environmental cost compared to other products of animal origin is leading to the search for ways to minimize the

Table 6
Means of non-carcass components of lambs classified by residual food intake (RFI) and residual intake and gain (RIG).

	RFI				RIG			
	EFI (RFI-)	MED (RFI±)	INEF (RFI+)	*P*- value	EFI (RIG+)	MED (RIG±)	INEF (RIG-)	*P*- value
	n = 7	n = 8	n = 5		n = 5	n = 11	n = 4	
Weight (Kg)								
Skin	5.12 ± 0.21	5.02 ± 0.20	4.81 ± 0.25	0.650	5.35 ± 0.22	5.02 ± 0.15	4.51 ± 0.24	0.060
RepA	0.73 ± 0.09	0.74 ± 0.08	0.82 ± 0.11	0.754	0.79 ± 0.10	0.70 ± 0.07	0.87 ± 0.12	0.434
Kidney	0.14 ± 0.01	0.14 ± 0.01	0.16 ± 0.01	0.489	0.15 ± 0.01	0.14 ± 0.01	0.15 ± 0.01	0.590
RPF	1.40 ± 0.21	1.54 ± 0.20	1.42 ± 0.25	0.873	1.27 ± 0.24	1.54 ± 0.16	1.48 ± 0.27	0.670
Spleen	0.24 ± 0.07	0.11 ± 0.06	0.11 ± 0.08	0.288	0.12 ± 0.08	0.19 ± 0.06	0.10 ± 0.09	0.644
RA	1.04 ± 0.11	1.09 ± 0.10	1.26 ± 0.13	0.448	1.02 ± 0.13	1.15 ± 0.09	1.14 ± 0.15	0.727
Heart	0.24 ± 0.02	0.26 ± 0.02	0.26 ± 0.02	0.708	0.27 ± 0.02	0.25 ± 0.01	0.24 ± 0.02	0.528
Head	2.88 ± 0.17	3.07 ± 0.16	3.20 ± 0.20	0.459	2.75 ± 0.19	3.15 ± 0.13	3.07 ± 0.21	0.251
Feet	1.19 ± 0.05	1.17 ± 0.05	1.24 ± 0.06	0.667	1.21 ± 0.06	1.20 ± 0.04	1.14 ± 0.07	0.728
Liver	1.17 ± 0.07	1.06 ± 0.07	1.04 ± 0.09	0.469	1.23 ± 0.08	1.07 ± 0.06	0.99 ± 0.09	0.146
TGIf	10.76 ± 0.87	10.92 ± 0.82	10.99 ± 1.03	0.984	11.26 ± 1.03	10.74 ± 0.69	10.80 ± 1.15	0.915
TGIe	7.61 ± 0.53	6.79 ± 0.50	6.43 ± 0.63	0.336	7.68 ± 0.64	6.86 ± 0.43	6.50 ± 0.72	0.440
Measurements (m)								
Duodenum and jejunum	25.77 ± 1.18	25.91 ± 1.10	26.44 ± 1.39	0.931	26.58 ± 1.39	25.90 ± 0.93	25.50 ± 1.55	0.868
Íleum	0.51 ± 0.08	0.47 ± 0.07	0.37 ± 0.09	0.506	0.41 ± 0.08	0.54 ± 0.05	0.30 ± 0.09	0.113
Cecum	1.24 ± 0.07	1.15 ± 0.07	1.25 ± 0.09	0.578	1.22 ± 0.09	1.21 ± 0.06	1.17 ± 0.10	0.941
Colon	3.73 ± 0.34	3.62 ± 0.32	3.86 ± 0.40	0.897	3.77 ± 0.40	3.65 ± 0.27	3.85 ± 0.45	0.916
Rectum	1.87 ± 0.28	1.65 ± 0.26	1.91 ± 0.33	0.777	1.54 ± 0.32	1.98 ± 0.21	1.59 ± 0.36	0.450

Means followed by different letters in the lines are statistically different by the Tukey test with a probability level of 5%. n = number of animals classified as efficient, medium or less efficient, out of a total of 20 animals slaughtered out of a total of 40 animals used to estimate the RFI and RIG. EFI = efficient, MED = medium, INEF = inefficient, RepA = reproductive apparatus with urinary vesicle, RPF = renal pelvic fat, RA = respiratory apparatus, TGIf = tract full gastrointestinal, TGIe = empty gastrointestinal tract.

Table 7
Qualitative characteristics of lamb meat classified by residual food consumption (RFI) and by residual intake and gain (RIG).

	RFI				RIG			
	EFI (RFI-)	MED (RFI±)	INEF (RFI+)	*P*- value	EFI (RIG+)	MED (RIG±)	INEF (RIG-)	*P*- value
	n = 7	n = 8	n = 5		n = 5	n = 11	n = 4	
pH 0	6.12 ± 0.12	6.08 ± 0.11	6.06 ± 0.14	0.950	6.32 ± 0.12	6.05 ± 0.08	5.92 ± 0.14	0.098
pH 24	5.64 ± 0.05	5.63 ± 0.05	5.68 ± 0.06	0.815	5.62 ± 0.06	5.65 ± 0.04	5.67 ± 0.07	0.876
T°0	27.74 ± 0.77	28.25 ± 0.72	27.80 ± 0.91	0.873	28.24 ± 0.91	27.77 ± 0.62	28.13 ± 1.02	0.899
T°24	12.84 ± 0.55	11.51 ± 0.52	13.28 ± 0.65	0.096	12.08 ± 0.74	12.61 ± 0.50	12.33 ± 0.83	0.835
L*	41.99 ± 0.95	41.15 ± 0.89	41.84 ± 1.12	0.789	42.12 ± 1.10	41.80 ± 0.74	40.48 ± 1.23	0.579
a*	13.27 ± 0.53	13.07 ± 0.50	13.28 ± 0.63	0.953	13.25 ± 0.63	13.21 ± 0.43	13.08 ± 0.71	0.983
b*	13.00 ± 0.75	12.70 ± 0.70	13.24 ± 0.88	0.885	12.80 ± 0.86	13.34 ± 0.58	12.04 ± 0.96	0.513
SF	31.1^{a} ± 2.95	21.1^{ab} ± 2.76	17.0^{b} ± 3.49	0.015	25.2 ± 3.80	26.3 ± 2.56	13.9 ± 4.25	0.063
CL	33.82 ± 1.92	29.72 ± 1.79	27.50 ± 2.27	0.115	30.16 ± 2.57	31.04 ± 1.73	29.93 ± 2.87	0.929
EvL	25.59 ± 1.80	21.52 ± 1.68	19.39 ± 2.13	0.096	21.01 ± 2.38	23.48 ± 1.60	21.24 ± 2.66	0.620
DL	8.23 ± 0.66	8.19 ± 0.62	8.10 ± 0.78	0.992	9.15 ± 0.71	7.56 ± 0.48	8.69 ± 0.79	0.165

Means followed by different letters in the lines are statistically different by the Tukey test with a probability level of 5%. n = number of animals classified as efficient, medium or less efficient, out of a total of 20 animals slaughtered out of a total of 40 animals used to estimate the RFI and RIG. EFI = efficient, MED = medium, INEF = inefficient, $T^{o}0$ = initial temperature (°C), $T^{o}24$ = muscle temperature after 24 h (°C), L* = luminance, a* = proportion of red, b* = proportion of yellow, SF = shear force (N), CL = cooking losses (%), EvL = evaporation losses (%), DL = drainage losses (%).

Table 8
Physical-chemical analysis of the *Longissimus lumborum* muscle as a function of residual food consumption (RFI) and by residual intake and gain (RIG).

	RFI				RIG			
	EFI (RFI-)	MED (RFI±)	INEF (RFI+)	*P*- value	EFI (RIG+)	MED (RIG±)	INEF (RIG-)	*P*- value
	n = 7	n = 8	n = 5		n = 5	n = 11	n = 4	
DM	23.58 ± 0.28	23.93 ± 0.26	24.03 ± 0.33	0.535	23.65 ± 0.31	23.70 ± 0.21	24.41 ± 0.31	0.211
CP	20.52 ± 0.83	20.64 ± 0.77	20.48 ± 0.98	0.388	20.48 ± 0.96	20.52 ± 0.64	20.66 ± 1.07	0.259
EE	1.78 ± 0.64	1.89 ± 0.60	2.03 ± 0.76	0.648	1.78 ± 0.75	1.84 ± 0.50	2.14 ± 0.83	0.517
MM	1.24 ± 0.21	1.20 ± 0.20	1.20 ± 0.25	0.652	1.24 ± 0.25	1.20 ± 0.17	1.21 ± 0.28	0.742

Means followed by different letters in the lines are statistically different by the Tukey test with a probability level of 5%. n = number of animals classified as efficient, medium or less efficient, out of a total of 20 animals slaughtered out of a total of 40 animals used to estimate the RFI and RIG. EFI = efficient, MED = medium, INEF = inefficient, DM = dry matter, CP = crude protein, EE = ether extract, MM = mineral matter.

environmental impact and maximize animal production (Salami et al., 2019; Vasconcelos-Filho et al., 2021). Less feed needed for similar or higher production levels is both attractive to producers and benefits the environment representing a clear advantage for livestock breeding and the planet. This study presents production and meat quality indicators of Santa Ines sheep consistent with the current demands for the production of animal protein.

Feedlot studies of cattle have shown that a 10% improvement in average daily gain (ADG) as a result of a 7% increase in feed consumption improved profitability by 18%, while a 10% improvement in feed efficiency resulted in a 43% increase in profits. Thus, efforts to improve the efficiency of feed/forage use will have a significant impact on reducing input costs for meat production (Fox, Tedeschi, & Guiroy, 2001). In the same line of thought, Amarilho-Silveira et al. (2022) reported that understanding the role of feed intake (FI) and growth rate in feed efficiency is indispensable to select economically efficient sheep. Cockrum, Stobart, Lake, and Cammack (2013) reported the savings that can be achieved with sheep, of different breeds, selected by the RFI, indicating a cost decrease of >$170/year/ram.

In this study, the animals in the RFI+ and RIG- groups, that is, the inefficient ones, consumed 33% and 23% more dry matter in relation to live weight than the efficient animals, despite having the same weight gain (approximately 230 g/day). These results demonstrate a direct advantage for the production system and an indirect advantage for the environment in the case of efficient animals. Working with Texel lambs, Rocha et al. (2018) found DMI of 9% less for the RFI- animals, a value lower than that found in our study. Variations in DMI among animals of different classes of feed efficiency are associated with several biological processes and environmental factors that regulate feeding and growth (Herd & Arthur, 2009). We believe that the use of the automated feeder in this experiment provided greater accuracy in consumption measurements and subsequent DMI calculations, and could be considered as one of the factors responsible, at least in part, for the differences found in relation to the reviewed literature. In studies carried out with whiteface (WB; $n = 183$; 7.00 ± 0.78 months of age) and meat sheep breeds (MB; $n = 147$; 4.14 ± 0.33 months of age) (Cockrum et al., 2013) and Hampshire ($n = 35$), Rambouillet ($n = 26$) and Suffolk ($n = 17$), initial live weight (BW) = 51.3 ± 1.2 kg (Ellison et al., 2022), both in automatic feeders, reported that more efficient rams consumed, on average, 1.20 kg/d and 1.45 kg/d less, respectively, than less efficient rams. Other studies have found 15–30% differences in DMI at similar levels of growth between high and low RFI groups of lambs, using similar automated feed intake recording equipment (Johnson, Miller, & Knowler, 2015; Redden, Surber, Grove, & Kott, 2013).

The overall performance achieved by groups, regardless of their efficiency, should also be highlighted. In a study using Australian lambs, ADG values from 169 g/day to 194 g/day were obtained according to breed (Merino or Dorset) (Flakemore et al., 2015). We highlight the outstanding performance of Santa Ines lambs in the confinement system. We believe that feeding in a collective pen with free access to food and water, along with the age of the animals and the forage:concentrate ratio used in this experiment may also have influenced the excellent performance obtained. On the other hand, in a feed efficiency test with the Pelibuey breed in Mexico, Arce-Recinos et al. (2022) found average daily weight gains of 230 to 260 g, with no difference ($p > 0.05$) between RFI classes, for animals kept in individual pens. However, the high variation in daily weight gain is well known, with numerous influences on this characteristic, such as genetics, management, nutrition, health, season of the year, age, and average weight, as can be seen in the studies of Redden et al. (2013), Paganoni et al. (2017), Freitas et al. (2021) and Arce-Recinos et al. (2022).

In terms of phenotypic variability of the studied efficiency traits, 32.5% of the animals were efficient and 25% inefficient when evaluated by RFI. As for the RIG, 25% of the animals were efficient and 27.5% inefficient. These proportions are similar to those found by Zhang et al. (2017), where 30.5% of the animals were efficient and 31.3% inefficient when the chosen measure was RFI. We believe that, as is this case for poultry, swine and cattle, genetics plays an important role in improving feed efficiency, and the observed phenotypic proportions have potential for selection for this type of trait in meat sheep. According to Azizi et al. (2021), in small ruminants, only limited data on heritability are available, although some reports confirm a promising role for the RFI trait in sheep. According to Amarilho-Silveira et al. (2022), since RFI is a hereditary trait, the selection for low RFI can be a useful tool to identify more lucrative animals, without affecting body weight traits, with variations in the RFI heritability coefficients from 0.11 to 0.45 in sheep (François et al., 2002, 2007; Tortereau et al., 2019, 2020). In another sense, the values of BCI1 and BCI2 confirmed the potential of the breed for meat production, considering the animals to have short lives (de Oliveira et al., 2020), that is, by body conformation and weight gain, the animals can be slaughtered at a very young age. Thus, the use of the RFI metric in selection programs for meat sheep is important.

Our findings confirmed the greater requirement in the discrimination of categories between groups according to the measure of feed efficiency used. Fewer animals were considered efficient when the applied measure was RIG. This shows that although RFI is an appropriate measure to assess feed efficiency, the fact that it is not correlated with weight gain can allow inclusion of animals with lower weight gains in the classification. In this sense, and according to the demand of the local market, for young animals (up to 8 months) with 40 to 50 kg live weight, the use of the RIG is recommended as a measure for the classification of meat sheep, aiming at greater feed efficiency with greater weight gain.

Morphometric measurements and characteristics of carcass and commercial cuts showed no differences in relation to the evaluated feed efficiency measures. Of the cuts studied, leg had the highest average (4.35 Kg) compared to the others. This result is important, since it confirms that the use of feed efficiency measures in sheep does not conflict with meat marketing aspects. This result is considered controversial when compared to studies in cattle, where measures of feed efficiency can be "misleading" by affecting the yield of higher value commercial cuts (Kelly et al., 2019). We emphasize that studies in sheep addressing measures of feed efficiency are still scarce, and so far few studies have evaluated their impact on selection through different progenies, on carcass, meat, and reproductive traits, among others. The controversial issue presented here should be understood as a warning about future approaches considering not only the animal's weight in the equations of efficiency measures, but the yields of the cuts as a measure of the model's adjustment. However, some studies have analyzed the genetic parameters for feed efficiency in sheep and their effects on traits of economic interest (Tortereau et al., 2020), while others have considered several parameters such as the incorporation of sex, genetic group, feed efficiency, loin eye area, subcutaneous fat thickness, prediction of carcass composition, water intake, food prior to evaluation, feeder, among others, in the model to estimate RFI (Cockrum et al., 2013; Durunna et al., 2011; Freitas et al., 2020, 2021; Johnson et al., 2015; Johnson, Miller, & Knowler, 2016).

Perhaps the most expected result in genetic improvement after the implementation of feed efficiency measures in populations is the absence of discrimination effects of carcass and meat characteristics. In this study, the characteristics involving meat quality were not affected by the feed efficiency measures used. The physical and sensory characteristics of meat can be affected by pH, which is one of the main factors that affect meat quality. In this study, the pH of efficient, moderate and inefficient animals according to RFI and RIG were within the range considered adequate, which is between 5.4 and 5.6 after cooling, and around 7 right after slaughter (Cezar & Sousa, 2018). Montelli et al. (2021) also did not observe differences in the pH of the meat of sheep from different classes of RFI and RIG, and the results found were between 5.4 and 5.8.

The greater shear force obtained by the RFI- animals in this experiment could be explained by the lower consumption of concentrate by the animals in this category. Inefficient animals consumed 0.7 kg/day more than efficient ones. Priolo, Micol, Agabriel, Prache, and Dransfield (2002) stated that lambs finished with a high level of concentrate in the diet may produce more tender meat, since a diet rich in concentrate results in meat with higher intramuscular fat content. In turn, intramuscular fat indirectly influences meat tenderness, by separating and diluting collagen fibers and disrupting the connective tissue structure (Hopkins, Allingham, Colgrave, & Van De Ven, 2013). However, it should be noted that the animals received the same 90% concentrate diet and that the intramuscular fat content was not evaluated in this work, which makes the correct understanding of this finding difficult. Other experiments should be carried out to better elucidate to this finding. Although animals efficient by RFI had less tender meat than inefficient ones, the values for both categories were lower than the breed average (34.32 N) (Ribeiro, de Castro, Moraes, & Marestone, 2020), and were considered tender for sheep meat (22.36 to 35.6 N) (Cezar & Sousa, 2018). Animals selected according to the RIG showed no differences in shear force (SF) ($P = 0.06$) regarding the efficiency categories (mean SF = 23.58 N), indicating that this measure, which includes the metabolic average live weight, could also select indirectly animals with softer meat compared to RFI. However, it is important to point out that this study used a small sample size and this characteristic (SF) presented a variation coefficient of 33%. Therefore, these results should be understood as preliminary and further studies should be performed to confirm these findings.

Another aspect of important commercial value in sheep meat is meat color. Depending on the country or region, there are consumption preferences regarding these variations. In general, the color space defined by the CIE (Commission Internationale de l'Éclairage) and adapted for sheep meat including the values of L* (lightness), a* (redness) and b* (yellowness) in all evaluated groups was found to be within the limit values for the breed (Ribeiro et al., 2020). Mean values of 41.56 (L*), 13.19 (a*) and 12.85 (b*) in the groups, regardless of the classification according to feed efficiency, indicated meat with adequate lightness and red and yellow color accepted by Brazilian consumers (Issakowicz et al., 2018; Landim, Castanheira, Clorinda, & Fioravanti, 2011; Ribeiro et al., 2020). Dorper sheep raised in Australia showed differences mainly in yellow color, with a mean of b* = 5.49 (Villatoro et al., 2021). The more yellowish color of the meat in the animals in this study can be attributed to different factors, but we highlight the breed pattern as being important, because the meat from Santa Ines sheep usually varies between 8.5 and 13.9 (Ribeiro et al., 2020).

In this study there was no variation in relation to non-carcass components. This result is controversial because in sheep there are already similar results (Rocha et al., 2018) and different ones (Montelli et al., 2021; Zhang et al., 2017). In cattle, the predominant results point to differences in non-carcass components according to feed efficiency classes (Montanholi et al., 2013; Montanholi et al., 2017; Nascimento et al., 2016). Feed efficiency is a complex multifactorial characteristic in meat animals and inter-animal variation results from the interaction of many biological processes, in turn influenced by the physiological state and management regime (Kenny, Fitzsimons, Waters, & McGee, 2018). The scarcity of studies involving feed efficiency measures and their relationship with non-carcass components does not allow consensus on the physiological factors and mechanisms involved in the efficiency of feed intake. For example, Zhang et al. (2017) reported lower liver, lung, stomach, and intestinal tract weights in lambs with low RFI, which were associated with lower energy intake and metabolic rate. We used animals with initial age of 187 ± 30 days and average initial weight of 44.5 ± 4.1 kg. This factor differentiates our population from those of other works involving sheep. We believe that age/initial weight influenced the processes of fat deposition and ontogenic growth of organs and viscera, which may explain, at least in part, the results obtained in this work. Studies of allometric ontogenic growth in goats demonstrated that the development of non-carcass components was arithmetic with a marked decrease above 40 kg body weight (Vieira et al., 2018). We emphasize that despite the higher feed intake presented by inefficient animals, regardless of the classification measure used, this did not result in greater deposition of abdominal or peri-renal fat, indicating that this deposition depends on the animal's growth phase, not necessarily on the amount of energy ingested in the feed.

In the literature, few works are found in this area, associating efficiency measures (RFI and RIG) with carcass characteristics and meat evaluation, being, for the most part, experiments carried out with cattle, with a minority of projects conducted with sheep. Even in experiments with cattle, many studies were carried out with a not very expressive number of samples, due to the cost and the difficulty in being able to carry out the efficiency test followed by slaughter (Basarab et al., 2003; Bonilha et al., 2013; Fidelis et al., 2017; Lage et al., 2014; Reis et al., 2015; Silva et al., 2022), which is an even greater aggravating factor in experiments with sheep (Arce-Recinos et al., 2022; Carneiro et al., 2019; Zhang et al., 2017), which are even scarcer in the literature. Power calculations were carried out and showed that the number of animals used in this project was not enough to affirm that the differences for carcass and meat characteristics really do not exist. However, according to the power test, using our results for traits such as hot carcass weight it would be necessary to slaughter approximately 150 animals to have a type II error (β) of 20%, while for other traits such as pH and temperature at time 0, the number of animals slaughtered would have to be 500 for the same 20% error rate. This would be unfeasible because the average number of animals in most Brazilian sheep herds is smaller than 150. Thus, our findings must be interpreted with caution, since differences between the averages for the carcass and meat characteristics could exist, improving or not the quality in favor of more efficient animals. However, the current study serves as a basis for future experiments, and our findings add weight to similar findings already reported in the literature. Finally, we believe that selection for feed efficiency in sheep, regardless of the measure used, requires evaluations involving aspects other than meat and carcass quality. Global sheep production is growing strongly and consumption trends point to rising international sheep meat demand (Chikwanha, Vahmani, Muchenje, Dugan, & Mapiye, 2018). Aspects such as ingestive behavior, digestive efficiency, ruminal microbiota, energy and protein metabolism, basal metabolism and stressors must be evaluated in relation to the reduction of feed intake, as they are part of the main physiological functions in growing sheep.

5. Conclusion

The selection of sheep based on feed efficiency measures such as RFI and RIG does not compromise the performance or characteristics of the carcass and meat in a feedlot system. Reductions in dry matter consumption of up to 33% were found between sheep classified as high or low efficiency, even within the small population studied. According to the greater degree of restriction applied by the RIG and due to the importance of weight gain for production systems, this measure is recommended for the selection of meat sheep bred in confinement.

Author statement

Conception and design of study: Ricardo Lopes Dias da Costa, Wilder Hernando Ortiz Vega
Acquisition of data: Danielle Nunes Gurgeira, Charleni Crisóstomo, Luiza Vage Coelho Sartori, Gustavo Delmilho, Mauro Sartori Bueno, Ricardo Lopes Dias da Costa
Analysis and/or interpretation of data: Danielle Nunes Gurgeira, Claudia Cristina Paro de Paz, Ricardo Lopes Dias da Costa
Drafting the manuscript: Danielle Nunes Gurgeira, Charleni Crisóstomo, Wilder Hernando Ortiz Vega
Revising the manuscript critically for important intellectual content: Alfonso Juventino Chay-Canul, Claudia Cristina Paro de Paz, Héctor Javier Narvaez Bedoya
All authors approved the version of the manuscript to be published.

Consent for publication

All permissions were obtained before submission.

Declaration of Competing Interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

Acknowledgments

This study was supported by the Foundation for Research Support of the State of São Paulo (Proc. Fapesp 2018-09298-6) and Office to Coordinate Improvement of Higher Education Personnel (CAPES), Finance Code 001.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.meatsci.2022.108959.

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