




# Are physiological responses and infrared thermography reliable indicators of feed efficiency in Texel sheep under tropical conditions?

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## ABSTRACT

**Context.** Residual feed intake (RFI) and residual intake and gain (RIG) are widely used metrics to assess feed efficiency in sheep. However, their practical implementation in breeding programs remains limited owing to the high cost and complexity of individual feed intake measurements. Consequently, alternative indicators, such as physiological responses and infrared thermography (IRT), have been proposed as potential proxies for identifying animals with superior feed efficiency under different environmental conditions. **Aims.** This study aimed to evaluate the relationships between RFI and RIG classifications and physiological parameters, as well as surface body temperatures obtained via IRT, in Texel ewes exposed to natural heat stress. **Methods.** Thirty-nine young Texel ewes were monitored for 57 days in a covered facility equipped with an automated feeding and watering system with individual intake recording. Animals were classified into low, medium, and high-efficiency groups according to their RFI and RIG values. Physiological responses, including respiratory rate (RR), heart rate (HR), rectal temperature (RT), and the heat tolerance coefficient (HTC), were recorded. Additionally, surface temperatures of the eye, muzzle, hooves, and vulva were measured using infrared thermography (IRT). Statistical analyses included ANOVA and principal component analysis (PCA) to explore associations among traits. **Key results.** No significant differences were detected among RFI or RIG classes for RR, HR, RT, or HTC. Similarly, IRT-derived surface temperatures did not differ across efficiency classifications. PCA showed that RR and HTC explained the greatest proportion of total variance, whereas RFI and RIG contributed to other independent components. **Conclusions.** Neither physiological parameters nor IRT-based surface temperatures were effective indicators of feed efficiency in Texel ewes under natural heat stress. **Implications.** The results indicated that RFI and RIG cannot be accurately inferred from physiological or IRT variables under field conditions. Future research should integrate additional phenotypic and behavioral indicators to identify reliable, low-cost biomarkers for metabolic efficiency in sheep.

**Keywords:** heat detection, infrared imagens, livestock precision farming, residual feed intake, residual intake and gain, thermal sensor, thermal stress, wool sheep.

## Introduction

Importing dual-purpose sheep breeds, mainly for meat, from European countries is a common practice among farmers in tropical regions aiming to improve traits of economic interest. In tropical climates such as in Brazil, wool-coated animals such as sheep face heightened thermal challenges. The thermoregulatory responses of wool versus hair sheep breeds can differ substantially, even in shorn individuals (Tüfekci and Sejian 2023). However, this pattern is not always consistent, because some wool breeds raised in hot environments also demonstrate heat tolerance (Bahadi *et al.* 2023).

The Texel breed was introduced in Brazil approximately the 1950s, with a population increase during the 1970s, according to the Brazilian Texel Breeders Association. It originated from Texel Island in the Netherlands. As reported by Wojtas *et al.* (2014), wool acts as a thermal barrier, limiting evaporative heat loss and consequently reducing the efficiency of

thermoregulation via sweating. In tropical conditions, heat stress can lead to reduced feed intake and metabolic alterations in ruminants (van Wettere *et al.* 2021; Matos *et al.* 2024; Zhang *et al.* 2024). Notably, heat stress may also result from excessive ingestion of feed or water, particularly in confined systems (Ferreira *et al.* 2025). Rumination and associated digestive processes generate endogenous heat (Barbosa *et al.* 2024), and excessive environmental heat absorption can impair animal performance (Ferreira *et al.* 2019; Sartori *et al.* 2024).

In feed efficiency trials, sheep are allowed *ad libitum* feed intake, which may influence heat production and thermoregulatory effort. Hendriks *et al.* (2013) and Fontes *et al.* (2023) reported associations between residual feed intake (RFI; Koch *et al.* 1963) and heat tolerance, suggesting that animals with negative RFI values (i.e. more efficient) might possess better thermoregulatory capacity. Nonetheless, findings remain inconsistent. For instance, Silveira *et al.* (2023) observed an association between RFI and rectal temperature in bulls, whereas Thompson *et al.* (2018) found no changes in ocular and cheek surface temperatures in bulls across different RFI classifications.

The same hypothesis can be extended to residual intake and gain (RIG; Berry and Crowley 2012). However, no studies have directly assessed the relationship between RIG and physiological parameters such as respiratory rate, heart rate, or rectal temperature. Montelli *et al.* (2019) and Sartori *et al.* (2024) investigated stress-related biomarkers (including cortisol) and reported no significant differences across feed-efficiency groups based on RIG. Therefore, investigating associations between thermoregulatory traits and feed-efficiency estimates (RFI and RIG) may offer new insights into phenotypic indicators for identifying metabolically efficient animals in wool sheep populations.

We hypothesized that animals with greater feed efficiency would exhibit superior physiological indicators, such as lower respiratory and heart rates, and lower surface and core body temperatures when exposed to natural heat stress. Thus, this study aimed to evaluate the relationship between feed-efficiency classifications (RFI and RIG) and both physiological responses and infrared thermographic measurements in Texel ewes raised under naturally hot environmental conditions, so as to identify potential biomarkers of metabolic efficiency.

## Materials and methods

### Location

The experiment was conducted in the confined sheep sector of the Animal Science Institute (Instituto de Zootecnia), part of the São Paulo Agribusiness Technology Agency (APTA) under the State Secretariat of Agriculture and Supply. The facility is located in Nova Odessa, São Paulo, Brazil (22°46'39"S, 47°17'45"W; altitude 570 m).

### Animals and feed-efficiency test

Thirty-nine young Texel ewes were used in the study, with an initial average age of  $130 \pm 7.54$  days, from União do Brasil Farm. At the beginning of the adaptation period, animals had an initial bodyweight of  $28.9 \pm 3.2$  kg, reaching a final bodyweight of  $45.6 \pm 3.4$  kg at the end of the experimental period. Prior to data collection, the ewes underwent a 15-day adaptation period to the facilities and feeding system, followed by a 57-day experimental period.

Throughout the adaptation and experimental phases, animals exhibited a consistent and homogeneous bodyweight progression, with no evidence of abnormal growth patterns or management-related disturbances. On the basis of the observed bodyweight increase over the experimental period, the average daily gain was approximately  $0.29 \text{ kg day}^{-1}$ , indicating normal growth performance under the adopted nutritional and management conditions. These performance indicators were used exclusively for descriptive characterization of the experimental population and were not intended for inferential comparisons among treatments.

Animals were housed in a covered indoor facility (approximately 5 m in height), with a floor being covered with sugarcane bagasse. The animals were kept in 70 m<sup>2</sup> pens equipped with an automatic feeding system consisting of nine electronic feeders (4.4 sheep per feeder) and two automatic water troughs (20 sheep per trough). The system (Intergado Science<sup>®</sup>, Contagem, MG, Brazil) was integrated with an electronic scale and a radio frequency identification (RFID) system, allowing automatic animal identification and recording of individual feed intake. Additionally, the system enabled automatic bodyweight measurements each time the animals visited the water troughs. The capacity of each feeder can be adjusted to accommodate up to 10 sheep per feeder.

Both water and feed were offered *ad libitum*. The diet was a complete mixed ration formulated for finishing lambs, containing 15% Tifton 85 bermudagrass (*Cynodon* spp.) hay, ground corn, soybean meal, and mineral supplement (RC Dieta Total *para* Ovinos em Confinamento<sup>®</sup>, Coopermota, Cândido Mota, SP, Brazil). The chemical composition of the feed is presented in Table 1. The methods for chemical analysis of the feed are identified in the legend of the same table. This ensured unrestricted intake and allowed each animal to express its individual physical and metabolic feeding capacity.

### Data collection

#### Environmental characterization

Environmental conditions were monitored using a Highmed WBGT Meter (HMTGD-1800, Taiwan, China), with data being recorded twice daily (morning at ~8:00 am and afternoon at ~4:00 pm) during both periods (adaptation and trial; total of 64 days). These periods are presented as two distinct blocks in Fig. 1, so as to facilitate visualization of environmental variations throughout the experiment.

**Table 1.** Chemical composition of the total experimental diet for finishing lambs. Values expressed as % of dry matter.

Variable	Concentration (%)
Dry matter (as-fed-basis)	88.66
Crude protein	15.23
Ethereal extract	2.87
Mineral matter	5.80
Non-nitrogenous extractives	66.34
Non-fibrous carbohydrates	49.08
Acid detergent fiber	12.99
Neutral detergent fiber	31.04
Cellulose	9.55
Hemicellulose	8.60
Lignin	2.20
Total digestible nutrients	73.39

Legend: dry matter (Method No. 934.01), ether extract (Method No. 920.39), mineral matter (Method No. 942.05) according to AOAC (1990), crude protein according to Wiles *et al.* (1998), and non-nitrogenous extractives and non-fibrous extractives according to AOAC (1995). Crude fiber, acid detergent fiber, neutral detergent fiber, cellulose, hemicellulose, and lignin according to Van Soest *et al.* (1991). Total digestible nutrients according to National Research Council (NRC) 2001.

Although minor differences in environmental conditions were observed between the periods, they were not considered sufficient to significantly affect the animals' physiological responses. Measurements included air temperature (AT, °C), relative humidity (RH, %), black globe temperature (BGT, °C), and dew point temperature (DPT, °C). To characterize heat load, we calculated the temperature–humidity index (THI) by using the dry-bulb temperature ( $T_{db}$ , °C) and RH. The THI was

calculated according to the following equation proposed by Thom (1959):

$$THI = T_{db} - \{(0.31 - 0.31 \times RH) \times (AT - 14.4)\},$$

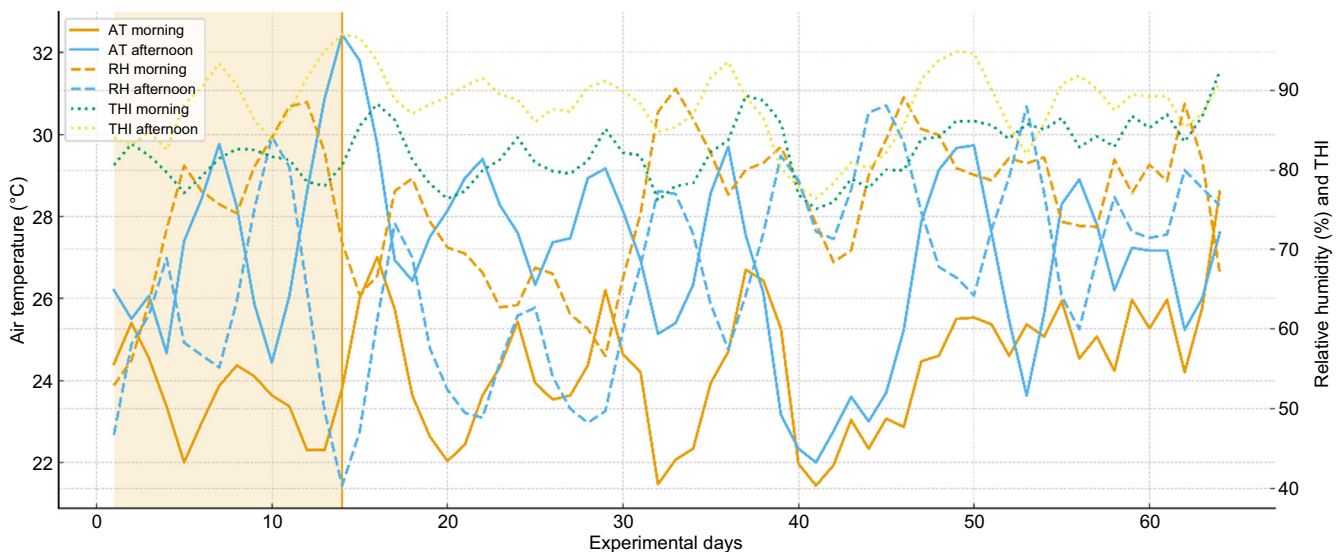
where  $T_{db}$  is the dry-bulb air temperature (°C) and RH is the relative humidity expressed as a decimal fraction. This formulation is widely used in biometeorological studies and yields THI values typically ranging from ~70 to 90 under tropical field conditions.

On the basis of this index, heat load was classified as absence of heat stress (THI < 72), mild heat stress (72–78), moderate heat stress (79–88), and severe heat stress ( $\geq 89$ ), following thresholds commonly adopted in livestock biometeorology (Thom 1959; Baêta and Souza 2010).

These categories are consistent with physiological response patterns described for sheep, particularly increases in respiratory rate and body temperature under elevated thermal load. For adult wool sheep maintained in still air and shade, the thermoneutral zone (TNZ) generally ranges from 10°C to 25°C, with a lower critical temperature (LCT) near 5–10°C (lower for animals with full fleece) and an upper critical temperature (UCT) ~25–28°C, which may decrease under conditions of high relative humidity and solar radiation. Above the UCT, marked increases in respiratory rate and rectal or skin temperatures are expected as primary heat-dissipation responses (Baêta and Souza 2010; Filho *et al.* 2011; Krishnan *et al.* 2023).

### Physiological parameters

Respiratory rate (RR, breaths  $\text{min}^{-1}$ ) was determined by visually counting flank movements for 30 s and multiplying the value by two. Heart rate (HR, beats  $\text{min}^{-1}$ ) was measured using a stethoscope (3M™ Littmann®, Shanghai, China) over a

**Fig. 1.** Daily variation in air temperature, relative humidity, and temperature–humidity index (THI) across 64 experimental days, measured in the morning (Period 1) and afternoon (Period 2). The first 14 days correspond to the adaptation period (shaded area).

30-s period, and the result was likewise doubled to obtain the final rate. Rectal temperature (RT, °C) was recorded with a veterinary digital thermometer (Multilaser, HCO70, China).

Physiological measurements were collected fortnightly over the 57-day experimental period, always in the morning, following a consistent procedure and sequence. To minimize potential handling bias, all assessments were performed by the same trained researcher and followed a standardized order of RR (the most sensitive parameter), HR, and then RT. Animals were gently restrained in small groups (4–6 animals) to reduce agitation and stress during measurement.

The heat tolerance coefficient (HTC) was calculated using the Benezra test (Muller 1989), as follows:

$$\text{HTC} = \left( \frac{\text{RT}}{39.1} \right) + \left( \frac{\text{RR}}{19} \right)$$

where 39.1°C and 19 breaths min<sup>-1</sup> are considered normal values for sheep.

### Infrared thermography measures

Infrared thermographic measurements were taken before morning feeding, with animals being individually restrained. Thermal images were captured using a FLIR E54 camera (Estonia), with 320 × 240 pixel resolution, 0.5°C sensitivity, and a temperature range from -20°C to 350°C. The camera was positioned 0.50 m from the animal to measure the surface temperature of four anatomical regions, namely, eye, muzzle, hooves, and vulva (Fig. 2).

Emissivity was set at 0.98, and reflectance temperature at 20°C, following recommendations for animal skin and watery

surfaces (Montanholi *et al.* 2009). Image analysis was performed using SmartView 3 software (Fluke IR-Fusion Technology), which calculated the mean and standard deviation of the surface temperatures for each anatomical region.

### Performance and feed-efficiency classification

Data on feed consumption and bodyweight were automatically recorded by the Intergado<sup>®</sup> feeding system. Daily dry-matter intake (DMI, kg day<sup>-1</sup>) was calculated from the as-fed intake and the dry-matter concentration of the diet determined by bromatological analyses (88.66%). Observed DMI (DMI<sub>obs</sub>) was calculated as

$$\text{DMI}_{\text{obs}} = \text{As-fed intake} \times [\text{DM}(\%)/100].$$

Feed efficiency was evaluated through residual feed intake (RFI) and residual intake and gain (RIG) indices. RFI was computed according to Koch *et al.* (1963) as the residual from a multiple linear regression of observed DMI on metabolic bodyweight (MBW = BW<sup>0.75</sup>) and average daily gain (ADG):

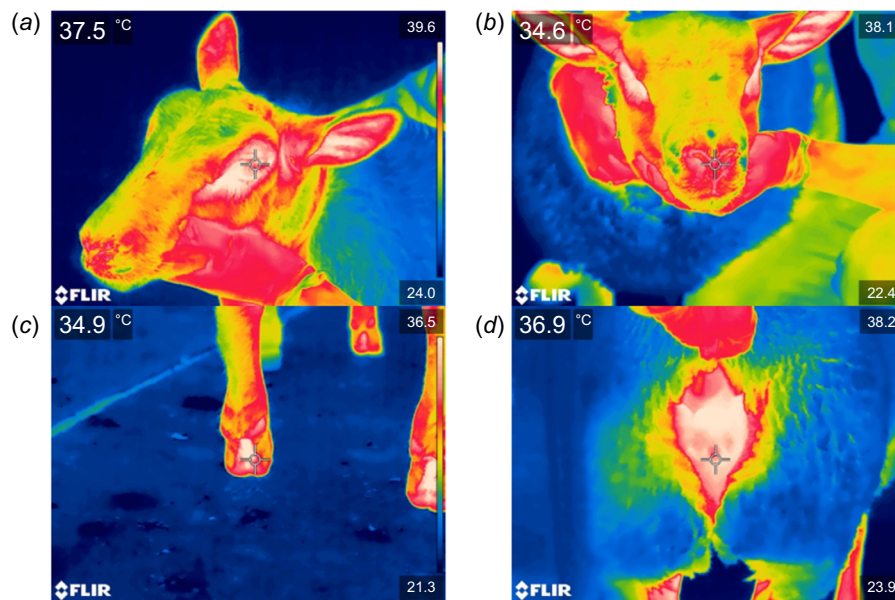
$$\text{DMI}_{\text{obs}} = \beta_0 + \beta_1 \times \text{MBW} + \beta_2 \times \text{ADG} + \epsilon,$$

where  $\epsilon$  represents the unexplained portion of intake (the residual), interpreted as RFI.

Animals with negative RFI values consume less feed than expected for their size and growth rate (i.e. are more efficient).

In the present study, the fitted model was as follows:

$$\begin{aligned} \text{DMI} = & 0.412 (\pm 0.162) + 0.087 (\pm 0.018) \times \text{MBW} \\ & + 2.231 (\pm 0.474) \times \text{ADG}, \end{aligned}$$



**Fig. 2.** Body regions used to determine surface temperature with infrared thermography for Texel ewes. (a) Eye, (b) muzzle, (c) hooves, and (d) vulva.

where coefficient of determination  $R^2 = 0.72$ , root mean-square error (RMSE) = 0.084 kg DM day<sup>-1</sup>, and  $n = 39$  animals.

Residuals met assumptions of normality and homoscedasticity (Shapiro–Wilk  $P > 0.10$ ; Levene  $P > 0.05$ ), and no multicollinearity was detected (VIF < 2).

Residual gain (RG) was calculated analogously, following Berry and Crowley (2012), by regressing ADG on MBW and DMI, as follows:

$$\text{ADG}_{\text{obs}} = \beta_0 + \beta_1 \times \text{DMI} + \beta_2 \times \text{MBW} + \epsilon,$$

yielding the fitted equation

$$\text{ADG} = -0.054 (\pm 0.018) + 0.086 (\pm 0.009) \times \text{DMI} + 0.0019 (\pm 0.0007) \times \text{MBW},$$

where  $R^2 = 0.68$  and  $\text{RMSE} = 0.015$  kg day<sup>-1</sup>.

Positive RG values indicate animals that gained more weight than expected for their feed intake and body size. Finally, the residual intake and gain (RIG) index was derived as

$$\text{RIG} = (-\text{RFI}) + \text{RG},$$

providing a composite efficiency score that rewards animals that both eat less and grow faster than expected.

To enable categorical comparisons, RFI and RIG values were standardized (mean = 0, s.d. = 1) by using the standard procedure (SAS 2012). Animals were classified into the following three feed-efficiency groups on the basis of  $\pm 0.5$  s.d. from the mean: low-efficiency,  $< -0.5$  s.d.; medium-efficiency,  $\pm 0.5$  s.d.; and high-efficiency,  $> +0.5$  s.d. The number of animals per class was as follows: low-RFI = 14, medium-RFI = 13, high-RFI = 12, low-RIG = 11, medium-RIG = 15, and high-RIG = 13. These classifications were subsequently used to evaluate physiological and infrared thermographic responses.

## Statistical analyses

Data were analyzed using descriptive statistics and ANOVA via the generalized linear model (GLM) procedure in R (ver. 4.2.3., (R Core Team 2021)). The effects of RFI and RIG classification (low, medium, high) on physiological and IRT variables were evaluated. Physiological (respiratory rate, heart rate and rectal temperature) and IRT variables were averaged per animal across the experimental period prior to statistical analysis. This procedure ensured a single independent observation per animal. Means were compared using Tukey's test with a significance level of 5%, implemented via the *multcomp* package (ver. 1.4-25, <https://CRAN.R-project.org/package=multcomp>; Hothorn *et al.* 2008). To explore complex associations among variables and to reduce data dimensionality, principal component analysis (PCA) was performed using the *FactoMineR* package (ver. 2.9, <https://CRAN.R-project.org/package=FactoMineR>; Lê *et al.* 2008)

and visualized with *Factoextra* (ver. 1.0.7., <https://CRAN.R-project.org/package=factoextra>).

## Ethics approval

This experiment was approved by the Animal Use Ethics Committee of the Instituto de Zootecnia (CEUA/IZ), under Protocol number 369-2022.

## Results

Meteorological data recorded during the experimental period are shown in Fig. 1. The highest variations in AT occurred during the afternoon, ranging from 20°C to 34°C. RH was generally higher in the morning (~70%), although the difference between morning and afternoon diminished after Day 40. The THI values indicated that animals were exposed to consistent heat stress throughout the 57-day period, particularly in the afternoon, with average THI values being ~80. Additionally, the HTC remained high (between 5.83 and 6.33), reinforcing the occurrence of thermal discomfort. Environmental conditions during the adaptation and trial periods were similar across the entire experiment.

The physiological traits and HTC values for Texel ewes classified by RFI and RIG groups are shown in Table 2. Statistical analysis showed no significant effect of feed-efficiency classification (RFI or RIG) on RR, HR, RT, or HTC. The mean values remained consistent across low-, medium-, and high-efficiency groups, with no clear trends, suggesting differences in thermoregulatory capacity. Furthermore, the minimum and maximum values for these parameters were similar among groups. These findings suggest that physiological responses such as RR, HR, RT, and HTC are not sensitive

**Table 2.** Means and standard error of the mean ( $\pm$ s.e.m.) of the physiological traits of young Texel ewes ranked for residual feed intake (RFI) and residual intake and gain (RIG).

Trait	High-RFI	Medium-RFI	Low-RFI	P-value
<i>RFI</i>				
Respiratory rate (breaths min <sup>-1</sup> )	98.5 $\pm$ 5.4a	91.8 $\pm$ 5.6a	98.5 $\pm$ 5.4a	0.65
Heart rate (beats min <sup>-1</sup> )	121.3 $\pm$ 4.4a	120.7 $\pm$ 4.5a	120.9 $\pm$ 4.7a	0.99
Rectal temperature (°C)	39.9 $\pm$ 0.03a	40.0 $\pm$ 0.02a	39.8 $\pm$ 0.03a	0.18
Heat tolerance coefficient	6.2 $\pm$ 0.2a	5.8 $\pm$ 0.2a	5.9 $\pm$ 0.3a	0.65
<i>RIG</i>				
Respiratory rate (breaths min <sup>-1</sup> )	100.7 $\pm$ 5.5a	91.8 $\pm$ 5.2a	91.3 $\pm$ 6.0a	0.41
Heart rate (beats min <sup>-1</sup> )	124.4 $\pm$ 4.3a	114.2 $\pm$ 4.0a	126.3 $\pm$ 4.7a	0.10
Rectal temperature (°C)	40.0 $\pm$ 0.02a	39.8 $\pm$ 0.03a	39.9 $\pm$ 0.03a	0.27
Heat tolerance coefficient	6.3 $\pm$ 0.2a	5.8 $\pm$ 0.2a	5.8 $\pm$ 0.3a	0.40

Different letters within a row indicate a statistically significant difference (at  $P = 0.05$ ) between the means, as determined by Tukey test.

indicators of feed efficiency in this population under the studied conditions.

Table 3 presents the IRT measures for different body regions (eye, muzzle, hooves, and vulva) across RFI and RIG classification groups. No significant differences in surface temperature were observed among low-, medium-, and high-efficiency animals. Mean temperatures across all regions remained close to 30°C, with minor fluctuations across classifications. The maximum and minimum IRT values were also comparable among groups. A statistically significant difference was observed for hoof temperature among RIG groups ( $P = 0.026$ ); however, the biological relevance of this difference appears limited.

PCA results are illustrated in Fig. 3. The first four principal components explained 74.1% of the total variation. The biplot (Fig. 3b) showed that the first component was primarily associated with IRT measurements of the hooves and muzzle, whereas the second component was related to RR and HTC, together accounting for 45.5% of the total variance. The third component was associated with feed-efficiency indicators (RFI and RIG), and the fourth with RT and eye IRT. These results indicate that RR and HTC were the most informative traits under heat stress conditions, whereas RFI and RIG contributed less to the overall variation structure.

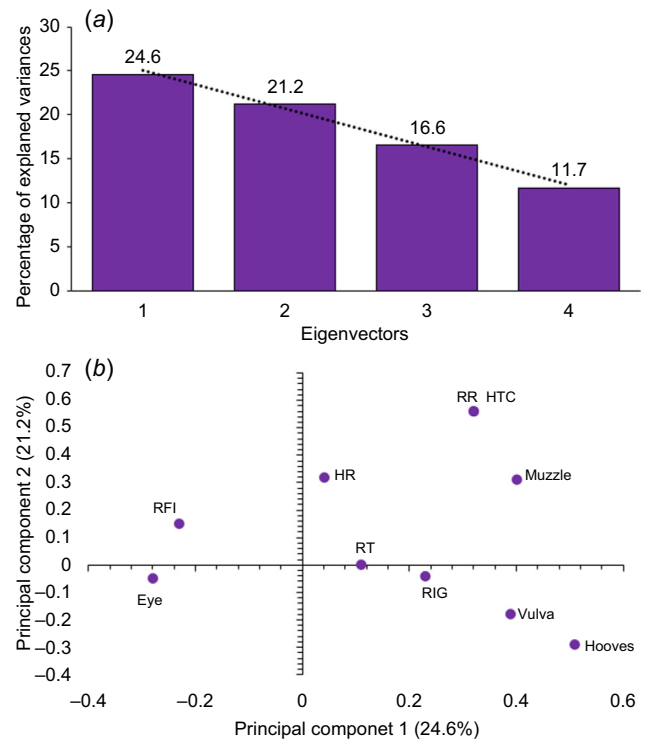
### Discussion

The environmental conditions during the experiment reflected a naturally hot climate, with frequent thermal stress as indicated by elevated THI values. Although originally developed for cattle, the Thom index (Thom 1959) has been widely applied in studies with sheep under tropical conditions, as a practical indicator of environmental heat load. Small ruminants, including sheep, are particularly vulnerable to high

**Table 3.** Means and standard errors of the mean ( $\pm$ s.e.m.) of the infrared thermographic temperature (IRT; °C) of the body regions of young Texel ewes ranked for residual feed intake (RFI) and residual intake and gain (RIG).

Trait	High-RFI	Medium-RFI	Low-RFI	P-value
<i>RFI</i>				
IRT eye	35.8 $\pm$ 0.1a	36.0 $\pm$ 0.1a	35.9 $\pm$ 0.1a	0.36
IRT muzzle	28.7 $\pm$ 0.6a	30.6 $\pm$ 0.6a	29.4 $\pm$ 0.6a	0.40
IRT hooves	28.4 $\pm$ 0.5a	27.7 $\pm$ 0.5a	26.5 $\pm$ 0.6a	0.27
IRT vulva	27.9 $\pm$ 0.7a	28.7 $\pm$ 0.7a	28.9 $\pm$ 0.6a	0.67
<i>RIG</i>				
IRT eye	35.9 $\pm$ 0.1a	35.8 $\pm$ 0.1a	36.1 $\pm$ 0.1a	0.19
IRT muzzle	30.5 $\pm$ 0.6a	29.1 $\pm$ 0.6a	29.3 $\pm$ 0.7a	0.27
IRT hooves	28.7 $\pm$ 0.5a	27.4 $\pm$ 0.5b	26.4 $\pm$ 0.6c	0.02
IRT vulva	28.1 $\pm$ 0.7a	29.0 $\pm$ 0.6a	28.3 $\pm$ 0.7a	0.55

Different letters within a row indicate a statistically significant difference (at  $P = 0.05$ ) between the means, as determined by Tukey test.



**Fig. 3.** Principal component analysis (PCA) of physiological traits (RR, respiratory rate; HR, heart rate; RT, rectal temperature; HTC, heat tolerance coefficient), infrared thermography (IRT) temperatures of different body regions (eye, muzzle, hooves, vulva), and feed-efficiency estimates (RFI, residual feed intake; RIG, residual intake and gain) in young Texel ewes under natural heat stress. (a) Variance explained by the first four principal components (PCs). (b) Biplot of PC1 and PC2, which together explained 45.5% of the total variance.

temperatures, which can impair both physiological function and productive performance (Baêta and Souza 2010; Filho et al. 2011). Therefore, understanding how these animals cope with heat is essential, especially when evaluating their feed efficiency in tropical systems (Mota-Rojas et al. 2021).

Despite clear signs of heat stress, such as elevated RR, HR, and RT, our analysis showed no significant differences in physiological traits among animals classified by RFI or RIG. These findings align with studies by Montelli et al. (2019) and Fontes et al. (2023), which also reported no significant physiological differences among efficiency groups in sheep. This pattern remained consistent throughout the experimental period, indicating stable physiological responses among the evaluated efficiency groups. In contrast, Matos et al. (2024) identified lower RR in more efficient lambs (RFI-), suggesting that breed, management conditions, or duration of exposure to stress may influence results.

This variability can be explained by physiological and morphological differences among breeds, environmental context, and duration of exposure to heat. Wool breeds generally have thicker fleece and lower sweat gland activity, which reduce evaporative cooling, and promote higher

respiratory rates when exposed to the same thermal load than those of hair breeds (Bahadi *et al.* 2023; Krishnan *et al.* 2023). Environmental factors such as air movement, humidity, and radiant heat modify the efficiency of convective and evaporative heat loss, directly influencing the magnitude of respiratory response (Baêta and Souza 2010). In addition, prolonged exposure to elevated temperatures can induce acclimation, reducing respiratory frequency because animals gradually adjust their metabolic heat production and peripheral blood flow (Mota-Rojas *et al.* 2021). Therefore, breed-specific morphology, ambient microclimate, and duration of heat exposure jointly determine the degree of respiratory response observed under stress conditions.

IRT did not show consistent differences in surface temperatures among efficiency groups. Whereas previous studies with cattle showed mixed results, some noting associations between thermographic measures and feed efficiency (Martello *et al.* 2016), and others not (Thompson *et al.* 2018), our findings support those of Crisóstomo *et al.* (2025), who also found limited predictive value of IRT for feed-efficiency classification in lambs.

Among the body regions assessed, eye temperatures exhibited the highest thermal stability, whereas the vulva and hooves showed greater variability. Despite a marginal difference in hoof temperature across RIG groups ( $P = 0.026$ ), the lack of consistent patterns across multiple traits suggests that surface temperature alone may not be a reliable biomarker. Although this hoof temperature difference was statistically significant, its biological interpretation is uncertain, because the magnitude of variation was small and inconsistent across other anatomical regions. One possible explanation is that hooves, being in direct contact with the floor, may reflect localized heat dissipation or environmental influences (e.g. floor temperature and contact time) rather than metabolic efficiency *per se*. Future studies incorporating repeated thermographic measurements, different flooring materials, or direct assessments of peripheral blood flow could help clarify whether hoof surface temperature can serve as a reliable biomarker or whether this finding merely reflects random variation.

The PCA provided additional insight, showing that RR and HTC were more closely associated with variation in the dataset than with RFI or RIG. These findings highlight the potential of RR and HTC as general indicators of thermal stress, but not necessarily of metabolic efficiency.

Taken together, the absence of physiological and thermographic differences among feed-efficiency groups suggests that alternative indicators, potentially including behavioral patterns, hydration status, or molecular biomarkers, should be explored to improve the identification of efficient animals under heat stress. Therefore, even though our findings are consistent with part of the existing literature, this work robustly reinforces that physiological responses and infrared thermography measurements are not reliable predictors of

feed efficiency in sheep under tropical conditions, thereby expanding the evidence base on this topic.

## Conclusions

The findings of this study did not support the initial hypothesis that more efficient Texel ewes (classified by RFI and RIG) would demonstrate superior physiological responses or lower surface body temperatures under naturally stressful thermal conditions. In the present conditions, physiological traits (RR, HT, RT, and HTC) as well as IRT measurements were not able to clearly distinguish animals with varying levels of feed efficiency. However, these results should be interpreted with caution, considering the sample size and the inherent variability of physiological responses under field conditions. Therefore, under the conditions of this study, these variables may have limited applicability as biomarkers for feed efficiency in confined Texel sheep. Future research integrating behavioral assessments, hydration dynamics, and molecular or genetic markers may contribute to a more comprehensive identification of metabolically efficient animals in tropical environments.

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**Data availability.** All data are available through the following links: <https://1drv.ms/x/s!AuEcvRDWRB1lywe0diM4H05FE08t>, <https://1drv.ms/x/s!AuEcvRDWRB1lywe0diM4H05FE08t>.

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