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APPLICATION OF THE MULTIVARIATE AND UNIVARIATE ANALYSES TO ESTIMATE THE FEED EFFICIENCY IN BEEF CATTLE

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Abstract
This study aimed to compare the univariate analyses (relationship between dry matter intake (DMI) and average daily gain (ADG), Kleiber ratio, and residual feed intake) and multivariate analysis (bionutritional index [BNI]) to determine feed efficiency. Were used a total of 160 cattle (individual data) and the analyzed variables were dry matter intake, weight gain, and body weight of the animals. We used five methods to evaluate feed efficiency, the BNI, FE, corrected feeding efficiency (corFE), Kleiber ratio (KR), and residual feed intake (RFI). Study 1 demonstrated that only the FE (p=0.0472) was significant, although the FE after the transformation of Box-Cox (corFE) (p=0.0642) showed a statistical trend. In studies 2, 3, and 5, we observed that BNI was the best biological efficiency indicator. In the study 4, we observed that the best indicators were FE (0.110; p=0.0281), corFE (0.380; p=0.0429), and RFI (0.465; p=0.0340) for the genders. However, corFE decreased the coefficient of variation in all studies. In conclusion, the use of the Box-Cox transformation is as efficient as the multivariate analysis in discriminating experimental groups (genetic groups, different levels of concentrate in the diet, and genders) concerning the other univariate analyzes.

Keywords: Intake. Performance. Ruminants. Statistical analysis.

1. Introduction

The feed supply represents the most important input to the cattle production system due to its high cost (Poppi et al. 2018). Dry matter intake (DMI) is an essential parameter in the formulation of diets to meet the nutritional requirements, predict the daily weight gain of the animals, and estimate the farm's profitability, mainly in feedlots. Thus, to reduce feed costs and use cheaper ingredients in the diets, it is necessary to keep the herd with efficient animals. The term efficiency refers to transforming the eaten feed into products such as meat and milk. Feed efficiency (FE) is not a new concept and, although research in this area is increasing, there are several definitions for feed efficiency (Kenny et al. 2018; Guinguina et al. 2019).

FE is usually expressed by the relationship between DMI and the average daily gain (ADG). However, some essential statistical aspects are commonly disregarded and may compromise inferences about FE. According to Guidoni (1994), DMI and ADG are mutually correlated continuous random variables that follow a normal probability distribution. The formation of a new variable may not have a normal distribution, and in this case, it approximates a non-parametric Cauchy distribution (Ruzgas et al. 2021).

For Detmann et al. (2005) and Lage et al. (2019), the relationship between DMI and ADG does not consider that a significant part of the feed can be used for maintenance requirements. Thus, variations in the portion of the feed used to maintain basal metabolism will result in biases that may not be easily detected if the production inference is made through this relationship.

Other calculations for determining FE using univariate analysis are also described, such as Kleiber ratio (Kleiber 1936) and residual feed intake (RFI) according to Martin et al. (2021). On the other hand, the linear combination of two variables in normal distribution produces a new variable with a normal distribution (Ruzgas et al. 2021). The multivariate techniques allow combining the multiple information of the experimental unit (Schmit et al. 2016). In this way, the linear combination between DMI and ADG using the first canonical variable can be indicated as an analytical option for the comparative assessment of feed efficiency (Detmann et al. 2005; Connor 2015). Despite the importance of feed efficiency, there are few comparative studies on the different ways of determining feed efficiency in cattle.

Therefore, we hypothesized that the results found for feed efficiency using univariate analysis might not be similar to those from a multivariate analysis. In this context, this study aimed to compare the univariate analyses (relationship between DMI and ADG, Kleiber ratio, and residual feed intake) with multivariate analysis (bionutritional index) to determine feed efficiency.

2. Material and Methods

We used the individual data collected from the appendix of five theses (Alves 2001; Veloso 2001; Gesualdi Junior 2003; Paulino 2006; Chizzotti 2007), all carried out using continuous designs. A total of 160 cattle was used in the present study, and the variables analyzed were dry matter intake, weight gain, and body weight of the animals. The description of the data used to analyze feed efficiencies is presented in Table 1.

Table 1. Descriptive statistics of the variables dry matter intake (DMI), average daily gain (ADG), and metabolic body weight ($BW^{0.75}$) extracted from the studies.

Study	Variables	Mean	Median	Maximum	Minimum	Standard deviation	N
1							12
	DMI	8.43	8.39	11.83	6.92	0.891	
	ADG	0.99	0.99	1.19	0.74	0.104	
	$BW^{0.75}$	84.69	85.08	91.59	76.16	3.788	
2							42
	DMI	7.93	7.85	10.77	5.88	0.867	
	ADG	0.98	0.88	1.93	0.42	0.314	
	$BW^{0.75}$	90.41	89.97	95.24	85.14	2.013	
3							22
	DMI	8.82	8.86	10.85	6.47	0.971	
	ADG	1.01	1.01	1.50	0.59	0.178	
	$BW^{0.75}$	93.56	93.19	109.29	80.92	6.285	
4							48
	DMI	7.39	7.45	8.70	6.23	0.388	
	ADG	1.06	1.08	1.36	0.61	0.182	
	$BW^{0.75}$	82.13	82.82	93.64	60.98	4.896	
5							36
	DMI	8.12	8.22	10.77	5.88	0.811	
	ADG	1.05	0.95	1.93	0.57	0.310	
	$BW^{0.75}$	82.56	84.66	93.64	60.98	4.952	

N = Individual ata used in each study.

Data descriptions

Study 1 – Alves (2001): Were used 12 steers, four Indubrasil, four F1 Holstein-Gir, and four F1 Holstein-Guzerat, with an initial body weight of 292.17 ± 6.2 kg. The animals were housed in individual pens and received diets with two crude protein levels until the slaughter. The diets were composed of Tifton grass hay (*Cynodon dactylon*), ground corn, soybean meal, urea/ammonium sulfate, dicalcium phosphate, and mineral premix, with a roughage-to-concentrate ratio of 60:40. The experimental design was completely randomized in a 3 x 2 factorial arrangement, with three genetic groups and two dietary crude protein levels. 24 animals (12 Indubrasil, 12 F1 Holstein-Gir, and 12 F1 Holstein-Guzerat) were used in this thesis. But, we only considered the growing animals in our study.

Study 2 – Veloso (2001): Fifty F1 Limousin x Nellore non-castrated steers were used with an initial body weight of 330 ± 4.8 kg. The animals were housed in individual pens and receiving diets with five levels of concentrate feed (25, 37.5, 50, 62.5, and 75%). The diets were formulated with Tifton grass hay (*Cynodon dactylon*), ground corn, soybean meal, urea/ammonium sulfate, limestone, dicalcium phosphate, sodium chloride, and mineral premix, with a roughage-to-concentrate ratio of 60:40. The experimental design was completely randomized in a 5 x 2 factorial arrangement, with five levels of concentrate feed and two feeding managements.

Study 3 – Gesualdi Junior (2003): Were used 22 animals, eight selected Nellore (NeS) and six selected Caracu (CaS) submitted to selection based on weight at 378 days of age (W378) at the end of the weight gain trial (WGT). Eight Nellores were also used, but the selection method was not applied (NeN). The animals were housed in individual pens and fed until the slaughter. The rations were formulated with corn silage, ground corn, cottonseed meal, urea/ammonium sulfate, monensin, and mineral mixture, with a 50:50 roughage-to-concentrate ratio. The contents of total digestible nutrients and metabolizable energy were 790 g/kg and 11.92 MJ/kg of dry matter (DM). The diet was adjusted weekly based on DMI and the DM percentage in the roughage and concentrate. The experimental design was completely randomized in a 2 x 3 factorial arrangement, with two feeding management, one restricted and the other ad libitum, and three genetic groups, selected Nellore, non-selected Nellore, and selected Caracu. In total, 44 animals were used (16 NeS, 12 NeN, and 16 CaS). But, we only considered the animals fed ad libitum in our study.

Study 4 – Paulino (2006): Were used 48 Nellore animals, 16 non-castrated males, 16 castrated males, and 16 females, with an initial body weight of 342.6 ± 3.8; 322.2 ± 5.7, and 296.9 ± 4.2 kg, respectively. The animals were distributed in individual pens and received concentrate feed in the proportions of 0.6 and 1.2% body weight until the slaughter. The diets were formulated with corn silage, ground corn, cottonseed meal, urea/ammonium sulfate, calcite limestone, sodium chloride, and mineral mixture, with a 85:15 roughage-to-concentrate ratio. The experimental design was completely randomized in a 2 x 3 factorial arrangement, with two levels of concentrate feed, 0.6 and 1.2% body weight, and three sex groups, non-castrated males, castrated males, and females.

Study 5 – Chizzotti (2007): A total of 36 F1 Nellore x Red Angus animals were used, 12 non-castrated males, 12 castrated males, and 12 females, with an initial body weight of 275 ± 7; 278 ± 8, and 228 ± 10 kg, respectively. The animals were distributed in individual pens and received two levels of concentrate in the proportions of 0.75 and 1.5% body weight until the slaughter. The diets were formulated with corn silage, ground corn, soybean meal, urea/ammonium sulfate, calcite limestone, sodium chloride, and mineral mixture, with a 70:30 roughage-to-concentrate ratio. The experimental design was completely randomized in a 2 x 3 factorial arrangement, with two levels of concentrate feed 0.75 and 1.5% body weight and three sex groups, non-castrated males, castrated males, and females.

Were used five methods to evaluate feed efficiency. The bionutricional efficiency (BNI) is represented by the first canonical variable, obtained through the dry matter intake and average daily gain. Feed efficiency (FE) is the ratio between the average daily gain and the daily dry matter intake. The corrected feeding efficiency (corFE) is the ratio between the average daily gain and the daily dry matter intake but submitted to data transformation. The Kleiber ratio (KR) was calculated using the ratio between average daily gain and metabolic body weight. Residual feed intake (RFI) is the difference between the actual consumption of dry matter and the amount of feed that the animal should consume based on its average body weight and weight gain speed. Thus, the most efficient animals are those with negative RFI (observed intake lower than the predicted intake for the observed gain), and the less efficient animals have positive RFI (observed intake higher than the predicted intake for the observed gain).

Bionutritional index (BNI)

The variables average daily gain (ADG) and dry matter intake (DMI) were considered together in a multivariate analysis MANOVA. According to Guidoni (1994), this procedure is a more sensitive method for discriminating the effect of treatments on the animal's nutritional performance than feed conversion or feed efficiency.

From the information generated by MANOVA, the non-normalized eigenvector value was estimated using the equation described by Seale (1966):

$$(E^{-1}H - \lambda_1 I)\tilde{v} = \begin{matrix}0\\0\end{matrix} \rightarrow (E^{-1}H)\tilde{v} = \lambda_1\tilde{v} \rightarrow (E^{-1}H)\begin{bmatrix}a\\b\end{bmatrix} = \lambda_1\begin{bmatrix}a\\b\end{bmatrix} \qquad \text{Eq.1}$$

In which, E^{-1} = inverse matrix of the sum of squares of residuals; H = matrix of the sum of squares of "treatments"; λ_1 = highest canonical eigenvector; $\tilde{v}$ = non-normalized eigenvector associated with the highest canonical eigenvector; a and b = canonical coefficients, and I = identity matrix.

Then, the normalization of the eigenvector of the eq. 1 was obtained according to the following restriction:

$$\widetilde{v}'n\, E\tilde{v}\, n = 1 \rightarrow a'\ b'\ E\begin{bmatrix}a'\\b'\end{bmatrix} = \begin{bmatrix}1\end{bmatrix} \qquad \text{Eq.2}$$

Where, $\widetilde{v}'n$ = normalized eigenvector associated with the highest canonical eigenvector; a' and b' = canonical coefficients of the normalized eigenvector $\tilde{v}$ and E = matrix of the sum of squares of residuals.

The CANDISC procedure from the SAS program was used, and the equation for Bionutricional Efficiency was determined:

$$BNI = a' \times DMI + b' \times ADG + e_{ij} \qquad \text{Eq.3}$$

Feed Efficiency (FE) and Corrected Feed Efficiency (corFE)

Feed efficiency is the ratio between average daily gain and daily dry matter intake.

$$FE = ADG/DMI \qquad \text{Eq.4}$$

However, according to Ruzgas et al. (2021), the ratio between two variables with normal distribution will not have a normal distribution, even if there is independence between them. Thus, if X and Y have a normal distribution, Z will have a Cauchy distribution ($\mu = 0$ e $\sigma^2 = 1$).

For the corrected feeding efficiency, we used the transformation of Box-Cox through the TRANSREG procedure from the SAS program:

$$y_i' = y_i' - 1/\lambda \text{ para } \lambda \neq 0 \qquad \text{Eq.5}$$
$$y_i' = \ln(y_{i)} \text{ para } \lambda = 0 \qquad \text{Eq.6}$$

Kleiber ratio (KR)

Kleiber ratio (Kleiber, 1961) was calculated using the ratio between average daily gain and metabolic body weight ($kg^{3/4}$).

$$KR = ADG/BW^{3/4} \qquad \text{Eq.7}$$

Residual feed intake (RFI)

Residual feed intake (RFI) was calculated as the difference between the average dry matter intake observed throughout the experiment and the intake estimated by a multiple regression:

$$\text{Estimated RFI} = \beta_0 + \beta_1 \times \text{MBW} + \beta_2 \times \text{ADG} + e_{ij} \qquad \text{Eq.8}$$

In which, MBW = average metabolic body weight ($kg^{0.75}$), GMD = average daily gain (kg/day), and e_{ij} = random error.

$$\text{RFI} = \text{Observed DMI} - \text{Estimated DMI} \qquad \text{Eq.9}$$

Animals that presented RFI values higher than the overall mean (+0.5 times the standard deviation) were classified as animals with high residual intake. Conversely, animals with RFI values lower than the overall mean (-0.5 times the standard deviation) were considered more efficient, as they presented low residual intake. This subdivision is commonly used in studies involving the evaluation of feed efficiency in beef cattle (Basarab et al. 2013).

The data of studies 1 and 3 were compared using the Tukey test with a significance level of 0.05, using the MIXED procedure (SAS University Edition, SAS Institute Inc., Cary, NC, USA). In studies 2, 4, and 5, we also analyzed the data through regression analysis with a significance level of 0.05, using the MIXED package (SAS University Edition, SAS Institute Inc., Cary, NC, USA). The studies were considered random effects.

The following statistical model was used:

$$Y_{ij}=\mu+\alpha_i+\beta_j+e_{ij}$$

In which: Y_{ij} is the observed value for the variable under study for the *i-th* variable; μ is the overall mean; α_i regarding the efficiencies, with i = 1,2,3,4,5; β_j is the effect the study, with j = 1,2,3,4,5; e_{ij} is the error associated with the observation Y_{ij}.

Pearson's correlation coefficient was used to measure the intensity of the linear relationship between the feed efficiencies using the procedure PROC CORR (SAS University Edition, SAS Institute Inc., Cary, NC, USA).

Were used the application of the basic descriptive measures to generate the profile of the dataset by the measurements of central tendency (mean and median) and dispersion (maximum, minimum, and standard deviation) using MEANS procedure of SAS.

3. Results

Performing the correlation analysis between the indicators of biological efficiency, dry matter intake (DMI) and average daily gain (ADG), we observed that BNI (0.49; $p < 0.0001$) and RFI (0.46; $p < 0.0001$) had a positive association with the DMI. However, FE (0.79; $p < 0.0001$), corFE (0.79; $p < 0.0001$), and KR (0.95; $p < 0.0001$) presented a strong association with ADG, although KR was also associated with DMI (Table 2). Between the indicators, BNI had a negative association with FE (-0.33; p = 0.0002) and corFE (-0.34; p = 0.0002). However, KR had a strong association with FE (0.77; $p < 0.0001$). The RFI, on the other hand, presented a strong association with corFE (0.77; $p < 0.0001$) (Table 2).

There was no study effect (p = 0.804), in this case, the data from each study were compared independently. Study 1 demonstrated that only the FE (p = 0.0472) was significant, although the corFE (p = 0.0642) showed a statistical trend, and the Indubrasil animals were more efficient using the FE as an indicator of biological efficiency. The RFI also showed that Indubrasil were the most efficient animals, despite not showing any statistical difference (-0.308; p = 0.3655). The protein levels in the diet did not affect the efficiency indicators (Table 3).

In study 2, only the RFI (p > 0.05) was not affected by the concentrate feed levels. We observed that BNI was the indicator with the lowest variation (5.59%), whereas the FE after the transformation of Box-Cox had the coefficient of variation (CV) decreased from 14.57 to 6.42%. However, the feeding management did not affect the biological efficiency indicators (Table 4).

Table 2. Pearson's correlation coefficients and probability values for feed efficiencies.

	DMI	ADG	BNI	FE	corFE	KR	RFI
DMI	1.00						
ADG	0.4891	1.00					
	<0.0001						
BNI	0.4925	-0.0865	1.00				
	<0.0001	0.3356					
FE	0.0397	0.7900	-0.3368	1.00			
	0.6720	<0.0001	0.0002				
corFE	0.0443	0.7955	-0.3434	0.9947	1.00		
	0.6362	<0.0001	0.0002	<0.0001			
KR	0.3909	0.9580	-0.1540	0.7792	-0.0870	1.00	
	<0.0001	<0.0001	0.1003	<0.0001	0.3530		
RFI	0.4626	0.1737	0.1571	-0.0980	0.7792	0.1376	1.00
	<0.0001	0.0623	0.0921	0.2950	<0.0001	0.1424	

DMI = Dry matter intake; ADG = Average daily gain; BNI = Bionutritional index; FE = feed efficiency (ratio between ADG and DMI); corFE = corrected FE; KR = Kleiber ratio; RFI = Residual feed intake.

Table 3. Evaluations of different methods of calculating feed efficiency as a function of genetic groups and protein content of the diets in finishing (Study 1).

Source of variation	DMI	ADG	BNI	FE	corFE	KR	RFI
P-values							
GG	0.345	0.6178	0.3416	0.0472	0.0642	0.1954	0.3655
PL	0.2773	0.235	0.2783	0.7913	0.8142	0.1356	0.30
GG X PL	0.6582	0.5328	0.6578	0.3588	0.3697	0.6221	0.5835
GG							
F1 (Hol/Gir)	8.05	0.95	21.620	0.118 [ab]	0.395	0.012	0.028
Indubrasil	7.95	1.05	21.357	0.131[a]	0.414	0.013	-0.308
F1 (Hol/Guzerá)	9.29	0.96	24.985	0.105[b]	0.375	0.011	0.743
PL							
12% CP	8.89	1.04	23.879	0.119	0.396	0.012	0.480
15 % CP	7.97	0.93	21.429	0.117	0.393	0.011	-0.171
overall mean	8.43	0.99	22.654	0.118	0.395	0.012	0.155
CV, %	10.57	10.57	10.58	10.07	4.46	9.49	381.40

DMI = Dry matter intake; ADG = Average daily gain; BNI = Bionutritional index; FE = feed efficiency (ratio between ADG and DMI); corFE = corrected FE; KR = Kleiber ratio; RFI = Residual feed intake; GG = Genetic group; PL = Protein levels; CP = Crude protein; CV = coefficient of variation. Means in the column, followed by different letters, differ according to the Tukey test (P<.05).

In study 3, only BNI (110,701; p = 0.0187) was significant among the biological efficiency indicators (Table 2). However, the Caracu breed was the most efficient and also had a higher DMI (9.58 kg/day; p = 0.0185) (Table 5), corroborating the correlation analysis (Table 2). We observed that FE after the transformation of Box-Cox had the coefficient of variation (CV) decreased from 17.79 to 8.06%.

In the study 4, we observed that the significant indicators were FE (0.110; p = 0.0281), corFE (0.380; p = 0.0429), and RFI (0.465; p = 0.0340) for the sex groups (Table 6). The most efficient animals were those with the highest ADG (ADG = 0.83 kg/day) (Table 6), corroborating the correlation analysis (Table 2). However, the RFI showed a statistical tendency (p = 0.0623) to associate with the ADG (Table 2). Applying the Box-Cox transformation, the coefficient of variation (CV) decreased from 11.63 to 5.04%. The concentrate levels did not affect the efficiency indicators (p > 0.05) (Table 6).

In study 5, only BNI (25,934; p < 0.0001) was significant among the biological efficiency indicators for the sex groups (Table 7). As in study 3, the most efficient animals had the highest DMI (9.44 kg/day; p = 0.001). The concentrate feed levels only did not affect the RFI (p = 0.9200) (Table 7).

Table 4. Evaluations of different methods of calculating feed efficiency as a function of concentrate levels and food management (Study 2).

Source of variation	DMI	ADG	BNI	FE	corFE	KR	RFI
P-value							
Linear	0.0167	0.0018	0.0005	<.0001	<.0001	0.0038	0.4361
Quadratic	0.1948	0.0222	0.3638	0.0278	0.0197	0.017	0.4015
FM	0.1282	0.4342	0.1570	0.8030	0.7080	0.3609	0.7982
CL x FM	0.2584	0.3521	0.1025	0.3596	0.1463	0.9854	0.6854
CL							
25	7.51	0.85	-12.074	0.113	0.386	0.009	0.336
37.5	7.67	1.04	-12.141	0.135	0.418	0.012	0.341
50	7.52	1.12	-11.808	0.148	0.435	0.012	0.085
62.5	7.24	1.20	-11.230	0.166	0.458	0.013	-0.303
75	7.04	1.11	-10.972	0.157	0.447	0.012	0.267
FM							
isoproteic	7.27	1.08	-11.836	0.145	0.427	0.011	0.182
non-isoproteic	7.52	1.09	-11.453	0.143	0.431	0.012	0.109
overall mean	7.39	1.06	-11.644	0.144	0.429	0.010	0.145
CV, %	5.25	17.08	5.59	14.57	6.42	16.39	329.15

DMI = Dry matter intake; ADG = Average daily gain; BNI = Bionutritional index; FE = feed efficiency (ratio between ADG and DMI); corFE = corrected FE; KR = Kleiber ratio; RFI = Residual feed intake; CL = Concentrate levels; FM = Food management; CV = coefficient of variation. Means in the column, followed by different letters, differ according to the Tukey test (P<.05).

Table 5. Evaluations of different methods of calculating feed efficiency as a function of genetic groups (Study 3).

Source of variation	DMI	ADG	BNI	FE	corFE	KR	RFI
P-value	0.0185	0.8408	0.0187	0.2530	0.2753	0.5013	0.7556
Genetic group							
Nellore	8.80 [b]	1.05	101.781[b]	0.120	0.400	0.011	0.190
Caracu	9.58[a]	0.99	110.701[a]	0.100	0.370	0.010	0.480
nonselected Nellore	7.81[c]	0.98	90.412[c]	0.130	0.410	0.012	0.380
overall mean	8.82	1.01	101.92	0.115	0.389	0.011	0.345
CV, %	11.01	17.62	11.00	17.79	8.06	18.14	181.50

DMI = Dry matter intake; ADG = Average daily gain; BNI = Bionutritional index; FE = feed efficiency (ratio between ADG and DMI); corFE = corrected FE; KR = Kleiber ratio; RFI = Residual feed intake; CV = coefficient of variation Means in the column, followed by different letters, differ according to the Tukey test (P<.05).

Table 6. Evaluations of different methods of calculating feed efficiency as a function of genders and concentrate levels (Study 4).

Source of variation	DMI	ADG	BNI	FE	corFE	KR	RFI
P-value							
CL	0.4602	0.6998	0.4762	0.8265	0.8063	0.9998	0.9102
Genders	0.4875	0.0444	0.4036	0.0281	0.0429	0.168	0.0340
Genders x CL	0.3584	0.5826	0.3521	0.2358	0.1195	0.3524	0.4752
Bull	7.55	0.83[a]	24.140	0.110[a]	0.380a	0.009	-0.465[a]
Steers	7.31	0.67[b]	23.202	0.094[ab]	0.358b	0.008	-0.181[b]
heifers	7.18	0.66[b]	22.751	0.091[b]	0.353b	0.008	-0.070[c]
CL							
0.6 % BW	7.25	0.71	23.051	0.097	0.364	0.008	-0.230
1.2 % BW	7.44	0.73	23.670	0.099	0.362	0.008	-0.245
overall mean	7.35	0.73	23.362	0.100	0.364	0.008	-0.238
CV, %	6.31	16.09	6.73	11.63	5.04	12.74	107.29

DMI = Dry matter intake; ADG = Average daily gain; BNI = Bionutritional index; FE = feed efficiency (ratio between ADG and DMI); corFE = corrected FE; KR = Kleiber ratio; RFI = Residual feed intake; CL = Concentrate levels; CV = coefficient of variation; BW = Body weight. Means in the column, followed by different letters, differ according to the Tukey test (P<.05).

4. Discussion

The most used measure to estimate individual feed efficiency is the ratio between ADG and DMI due to its simple calculation (Eq.4). For Detmann et al. (2005), although this relationship can be easily verified at the experimental unit level, it can provide different estimates of productive efficiency. The divergences seem to be more evident in experiments with cattle (possibly by the lower experimental precision of cattle trials compared to poultry trials, for example), suggesting that the proportion indexes cannot similarly evaluate the production trials. Besides, DMI and ADG are correlated continuous random variables ($r = 0.49$; $p < 0.0001$) and follow the normal probability distribution. According to Keene (1995), the ratio between two variables with normal distribution will not have a normal distribution, but Cauchy's distribution. Therefore, if the assumptions of normality and homoscedasticity are not met, the information obtained by statistical analysis can generate serious misunderstandings (Xu et al.,2013). When we applied the Box-Cox transformation (Eqs. 5 or 6) in the evaluated studies, the corFE values were higher than the FE. According to Freitas et al. (2002), this fact may be due to the transformation to reduce the data asymmetry coefficients, which probably reduced the CV of the corFE, increasing the accuracy of this variable.

Table 7. Evaluations of different methods of calculating feed efficiency as a function of genders and concentrate levels (Study 5).

Source of variation	DMI	ADG	BNI	FE	corFE	KR	RFI
P-value							
Genders	0.001	0.0952	<0.0001	0.4546	0.4547	0.2011	0.6523
CL	<0.0001	<0.0001	<0.0001	0.008	0.01	0.0005	0.9200
Gender x CL	0.3113	0.5385	0.004	0.8258	0.8508	0.5263	0.6960
Gender							
Bull	9.44^{a}	1.49	25.934^{a}	0.156	0.445	0.018	0.029
Steers	8.77^{a}	1.24	10.787^{b}	0.156	0.445	0.015	0.339
heifers	7.92^{b}	1.25	4.909^{c}	0.140	0.424	0.016	0.131
CL							
0.75 % BW	8.00^{b}	1.058b	12.710^{b}	0.133^{b}	0.415^{b}	0.0137^{b}	0.153
1.5 % BW	9.42^{a}	1.592a	15.044^{a}	0.169^{a}	0.461^{a}	0.0189^{a}	0.180
overall mean	8.71	1.32	13.88	0.151	0.438	0.016	0.166
CV, %	8.37	21.74	57.93	15.05	6.56	16.69	249.03

DMI = Dry matter intake; ADG = Average daily gain; BNI = Bionutritional index; FE = feed efficiency (ratio between ADG and DMI); corFE = corrected FE; KR = Kleiber ratio; RFI = Residual feed intake; CL = Concentrate levels; BW = Body weight; CV = coefficient of variation. Means in the column, followed by different letters, differ according to the Tukey test (P<.05).

Another way of estimating feed efficiency is by the Kleiber ratio (Eq. 7), which has the advantage of not requiring individual measurement of consumption, and it is used to identify animals with high growth efficiency related to body size. A high value indicates dilution in the maintenance requirements, and this means that the ADG increases at the expense of the increase in $BW^{3/4}$, consequently greater body growth without increasing the maintenance energy cost (Chaves 2013). However, the Kleiber ratio differed significantly ($p < 0.05$) in studies 2 and 5 (Table 3 and 6, respectively), the probable reason is that this ratio takes into account body weight and gain, and only in study 2 there was a difference for the ADG, the others were similar between the animals. Nkrumah et al. (2004) evaluated energy efficiencies and observed that the Kleiber ratio is not sensitive to identify differences between animals with similar weights and ADG.

The FE, corFE, and KR were highly correlated with average daily gain (Table 2), corroborating with Archer et al. (1999), which can result in a significant increase in the consumption and size of the animals (Herd et al. 2003), and within the production system, it would not be economically viable, since a cost reduction is a goal. Thus, in 8ficie of a new measure of feed efficiency that would make it possible to reduce feed costs without negatively affects productive aspects, Koch et al. (1963) suggested the residual feed intake. In our work, 8fic study 4 showed a statistical difference ($p = 0.0340$; Table 6), indicating that non-castrated males consumed less to produce an ADG similar to females and castrated males with the same metabolic size ($BW^{3/4}$), this means those animals required less energy for maintenance, corroborating the results found by Mello et al. (2010). Another fact that we observed was the high CV for this variable in all the evaluated studies, demonstrating an imprecision of this variable.

Mello et al. (2010) reported that values found for efficiency using univariate analysis might not be similar 8fic using multivariate analysis. So, BNI was used because it meets the premises of the normal Gauss-Markov model, taking advantage of collective information about variables and their discriminatory character (Guidoni 1994). Therefore, for Detmann et al. (2005), the linear combination between DMI and ADG applying the first canonical variable is an analytical option for the comparative evaluation of feed efficiency. The first canonical variable is the linear discriminant function of Fisher, that is, a linear combination that allows discrimination between classes or groups (Fisher 1938). This combination maximizes the variations between classes or groups and minimizes the intragroup variation (residual variance) (Fisher 1936). Accordingly, the first canonical variable 9ficien in animal production was called the bionutricional index (Euclides et al. 2001). Our study observed that BNI showed a statistical difference in studies 2, 3, and 5 (Tables 4, 5, and 7, respectively). Also, if we analyze the ADG and DMI from these studies independently, the efficient observed in the BNI may suggest that 9fic really exist, and the multivariate analysis is, in fact, a more efficient method for their discrimination.

5. Conclusions

The use of the Box-Cox transformation (corFE) is as efficient as the multivariate analysis (BNI) in discriminating experimental groups (genetic groups, different levels of concentrate in the diet and sex groups) concerning the other univariate analyzes (FE, KR, and RFI).

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