Livestock Science 274 (2023) 105268

Contents lists available at ScienceDirect

Livestock Science

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

Use of statistical models to determine the optimal concentration of metabolizable energy for growth performance of broiler chickens

F.O. Marx [a], M.V.N. Alvarez [b], L.S. Bassi [a,*], A.P. Félix [a], E.L. Krabbe [c], S.G. Oliveira [a], A. Maiorka [a]

[a] Department of Animal Science, Federal University of Paraná, Curitiba, PR 80035-050, Brazil
[b] Biotechnology Institute and Bioscience Institute, São Paulo State University, Botucatu, SP 18618-689, Brazil
[c] Embrapa Suínos e Aves, Concórdia, SC 89715-899, Brazil

HIGHLIGHTS

- Statistical models can be used to determine the optimal dietary concentration of metabolizable energy for broiler chickens.
- Different regression models can lead to distinguished interpretations of dietary energy recommendations.
- Quadratic polynomial regression model fit best the data in the grower phase for optimal feed conversion ratio (FCR).
- Linear response plateau model best fit the data in the finisher phase for optimal FCR.

ARTICLE INFO

Keywords:
Broiler chickens
Growth performance
Metabolizable energy
Optimal energy content
Statistical models

ABSTRACT

The formulation of diets that adequately meet energy requirements in the different phases of broiler chicken production is of the utmost importance. The objective of this study was to determine the optimal content of metabolizable energy (ME) for broiler chickens in various production phases using different statistical models. A total of 900 broiler chickens were assigned to 5 treatments with 9 replicates of 20 broiler chickens each from 21 to 42 d of age in a completely randomized design. Experimental diets were based on corn and soybean meal and formulated to meet the nutritional requirements of broiler chickens, except for ME requirements. Dietary treatments consisted of 5 pelleted/crushed diets with increasing levels of ME: T1 to T5 (2,850 to 3,250 kcal/kg), divided into grower (21 to 35 d) and finisher (35 to 42 d) phases. Feed intake (FI), body weight gain (BWG), feed conversion ratio (FCR), total energy intake, efficiency of energy use for BWG, and carcass and cuts yields were determined. The ideal ME content for best FCR was determined with the use of quadratic polynomial (QP), segmented, and linear response plateau models (LRP). In all evaluated periods, BWG was not influenced by ME, whereas FI and FCR decreased linearly with increasing ME. Total energy intake increased and the energy use efficiency for BWG decreased with greater ME ($P < 0.05$). Neither carcass nor cuts yields were influenced by dietary ME. The ideal dietary ME content differed between statistical models. In conclusion, based on FCR results, the QP regression model presented the best fit of the data in the grower phase, indicating an optimal content of metabolizable energy for feed conversion of 3,264 kcal/kg, whereas LRP presented the best data adjustment in the finisher phase, indicating 3,224 kcal/kg of ME as optimal.

1. Introduction

The genetic improvement of commercial broiler chickens has ultimately resulted in better productive performance characteristics and carcass quality, although at the cost of increased nutritional requirements. Energy is not a nutrient but is considered as one of the dietary cornerstone components (Sakomura and Rostagno, 2007) and represents a major cost factor in feed formulation (Mendes et al., 2004). The preparation of diets that meet energy requirements of broiler chickens as they undergo different phases of production is critical; the age of broiler chickens is a determining factor for the efficiency of diet utilization, as older broiler chickens may present greater nutrient

* Corresponding author.
E-mail address: lucas.bassi@ufpr.br (L.S. Bassi).

https://doi.org/10.1016/j.livsci.2023.105268
Received 8 October 2022; Received in revised form 20 April 2023; Accepted 30 May 2023
Available online 15 June 2023

digestibility due to the greater development of the digestive tract (Mello et al., 2009); thus, improving energy and nutrient utilization.

Poultry industry professionals are on a constant search for means to assist in the preparation of balanced diets, such as the statistical models typically used to determine optimal nutrient concentrations. In poultry production, linear models are often used for such purpose (Nunes et al., 2015; Pompeu et al., 2013) because of their convenient use in statistical programs and easy interpretation of results (Oviedo-Rondón and Waldroup, 2002; Pack et al., 2003). Other statistical models worth mentioning are the quadratic polynomial (QP), linear response plateau (LRP), and segmented models.

The QP regression model is commonly used in agricultural research due to its simplicity in performing the calculations and easy interpretation of biological phenomena (Nunes et al., 2004). It is characterized by a graph parabola of either increasing or decreasing order depending on the independent variable analyzed, indicating a maximum or minimum point. The LRP regression model combines linear responses with plateau points. In this model, the animal's response to increasing doses of limiting nutrients in the diet will go up until reaching a plateau, after which it becomes constant. Similarly, there is the also the segmented model. Both the LRP model and the segmented model are discontinuous, i.e., they form a new segment after the so-called "break point" - the segmented model may generate a new line, curve or plateau, whereas the LRP will necessarily generate a plateau (Portz et al., 2000; Sakomura and Rostagno, 2007).

The various statistical models and their intrinsic characteristics can generate conflicting results when estimating optimal inclusion rates of energy and nutrients or feed additives to poultry diets (Siqueira et al., 2009). Added to a lack of standardization regarding the selection of adequate models and a lack of proper evaluation of the models through statistical criteria, this can lead to a suboptimal energy utilization and impaired growth performance. The objective of this study was to evaluate the adequacy different statistical models used to determine the optimal dietary concentration of ME for broiler chicken diets during grower (21 to 35 d) and finisher (35 to 42 d) periods.

2. Material and methods

2.1. Animal husbandry and facilities

The study was conducted at the Brazilian Agricultural Research Corporation (Embrapa) Swine & Poultry facilities (Concórdia, SC, Brazil) and was carried out following the approval by the Ethics Committee on Animal Use of Embrapa Swine and Poultry. A total of 900 one-day-old male broiler chickens (Cobb 500; Cobb Brazil Ltda, SP, Brazil) were housed in 45 pens (2.06 m^2) with wood shavings as litter, equipped with a tubular feeder and nipple drinkers. Water and feed were provided ad libitum. Maximum and minimum thermometers were used to check the temperature daily. A continuous lighting program was set for the first 24 h, and the hours of light/day were gradually decreased according to the Cobb Broiler Management Manual (Cobb-Vantress, 2013). The room temperature was set to 32 °C at d 0 and weekly reduced to approximately 18 °C on d 42 of the experiment. The pens were inspected daily for removal of dead and culled broiler chickens, whose weight was used to adjust performance variables.

2.2. Experimental design and diets

A completely randomized design was conducted, with 5 treatments and 9 replications of 20 broiler chickens each. From 0 to 21 d of age, all

Table 1
Calculated nutritional composition of experimental diets.

Ingredients (%)	Grower phase					Finisher phase				
	Metabolizable energy (kcal/kg)					Metabolizable energy (kcal/kg)				
	2850	2950	3050	3150	3250	2850	2950	3050	3150	3250
Corn (7.5% crude protein)	56.00	56.00	56.00	56.00	56.00	59.04	59.04	59.04	59.04	59.04
Soybean meal (45% crude protein)	33.13	33.13	33.13	33.13	33.13	31.08	31.08	31.08	31.08	31.08
Soybean oil	2.34	3.48	4.61	5.75	6.89	1.76	2.90	4.03	5.17	6.31
Inert substance[1]	5.00	3.86	2.73	1.59	0.45	5.00	3.86	2.73	1.59	0.45
Dicalcium phosphate	1.26	1.26	1.26	1.26	1.26	1.01	1.01	1.01	1.01	1.01
Limestone	0.87	0.87	0.87	0.87	0.87	0.81	0.81	0.81	0.81	0.81
Sodium chloride	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
DL-Met	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Mycotoxin adsorbent	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
L-Lys	0.18	0.18	0.18	0.18	0.18	0.19	0.19	0.19	0.19	0.19
Vitamin premix[2]	0.10	0.10	0.10	0.10	0.10	0.07	0.07	0.07	0.07	0.07
Mineral premix[3]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
L-Thr	0.08	0.08	0.08	0.08	0.08	0.06	0.06	0.06	0.06	0.06
Choline chloride	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Antoxidant[4]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Coccidiostatic[5]	0.05	0.05	0.05	0.05	0.05	–	–	–	–	–
Colistin[6]	0.01	0.01	0.01	0.01	0.01	–	–	–	–	–
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition										
Metabolizable energy, kcal/kg	2850	2950	3050	3150	3250	2850	2950	3050	3150	3250
Crude protein,%	19.19	19.19	19.19	19.19	19.19	18.46	18.46	18.46	18.46	18.46
Ca,%	0.73	0.73	0.73	0.73	0.73	0.64	0.64	0.64	0.64	0.64
Digestible P,%	0.35	0.35	0.35	0.35	0.35	0.30	0.30	0.30	0.30	0.30
Total P,%	0.59	0.59	0.59	0.59	0.59	0.54	0.54	0.54	0.54	0.54

[1] kaolin (Mineração Itapeva Ltda.).
[2] Provided per kilogram of the diet, Grower phase: vitamin A: 9000 IU; vitamin D3, 2500 IU; vitamin E, 20 IU; vitamin K3, 2.5 mg; vitamin B1, 1.5 mg; vitamin B2, 6 mg; vitamin B2, 6 mg; vitamin B6, 3 mg; vitamin B12, 12 mcg; pantothenic acid, 0.012 g; niacin, 0.025 g; Folic acid, 0.8 mg; biotin, 0.06 mg. Finisher phase: vitamin A: 6300 IU; vitamin D3, 1750 IU; vitamin E, 14 IU; vitamin K3, 1.75 mg; vitamin B1, 1.05 mg; vitamin B2, 4.2 mg; vitamin B2, 4.2 mg; vitamin B6, 2.1 mg; vitamin B12, 8.4 mcg; pantothenic acid, 0.008 g; niacin, 0.018 g; folic acid, 0.56 mg; biotin, 0,04 mg.
[3] Provided per kilogram of the diet: Cu: 0.01 g; Fe, 0.05 g; Mn, 0.08 g; Co, 10 mg; I, 10 mg; Zn, 0.05 g; Se, 0.25 mg.
[4] Butylated hydroxytuolene 98% - BHT (Impextraco, Curitiba, PR, Brazil).
[5] Sodium monensin (Coban; Elanco Animal Health, Indiana, US).
[6] Colistin 4800 WP (Kepro, Woerden, Netherlands).

broiler chickens received the same basal diet. Afterwards, the broiler chickens were fed 1 of 5 experimental diets formulated with increasing levels of ME (modified via the inclusion rate of soybean oil), being 2850, 2950, 3050, 3150, and 3,250 kcal/kg (Table 1). The experimental period was divided into grower (21 to 35 d) and finisher (35 to 42 d) phases.

Diets were based on corn and soybean meal and met the nutritional requirements of broiler chickens on each phase, except for ME, which varied according to the treatments. The diets were pelleted using a pellet mill (Koppers Júnior C40; Koppers Company, Inc. Pittsburgh, PA, US) with capacity of 3 t/h operating with pressure of 2.4 kgf/cm^2 and conditioned at a temperature of 68 to 70°C for 15 s.

2.3. Growth performance

At d 21, all broiler chickens were weighed individually and the average live weight at the beginning of the experiment was 901 ± 21 g. Collected body weight, feed allowance, and feed refusal on d 21, 35, and 42 were used to calculate body weight gain (BWG), feed intake (FI), and feed conversion ratio (FCR). Total energy intake (TEI) was calculated for each period using FI and dietary energy content. Dietary energy utilization efficiency (EEWG) was determined as the ratio between energy intake and BWG, expressed as calorie intake per gram of BWG (Gopinger et al., 2017).

2.4. Carcass yield

At d 42, 2 broiler chickens per experimental unit (totaling 90) were randomly chosen and weighed. The broiler chickens were electrically stunned and killed after fasting for 12 h and subsequently plucked, eviscerated, and stored for 24 h in a cooling chamber (0 to 5ºC). After cooling, the carcasses were weighed and cut to determine carcass yield, breast yield, and abdominal fat percentage. The carcass yield was calculated as the difference between the weight of the cooled carcass and the live weight; the parts yield was calculated in relation to the carcass weight and expressed as a percentage.

2.5. Statistical models

To determine the optimal ME content, the data were adjusted using the QP and LRP regression models and segmented model, considering the FCR as the dependent variable and dietary ME content as the independent variable.

The evaluated models were as follows:

1 QP: $Y = \beta0 + \beta1X + \beta2\times^2$, where: Y = dependent variable; X = is the ME dietary content; β0 = intercept; β1 = coefficient and β2 = quadratic coefficient. The optimal ME content is obtained by: -β1/(2 × β2).
2 LRP: $Y = \beta0 + \beta1*(X - V)$, if $(X <= V)$, where β0 is intercept of the maximum response; β1 is the slope of the straight line before the breakpoint, and $(X <= V)$ is a Boolean expression (Gris and Schneider, 1993), as in: $(X <= V) = 1$ only if X, the dietary ME dietary, is less than or equal to V, the ME at the breakpoint of the function. $(X <$ or $= V) = 0$ if X is greater than V.
3 Segmented regression: $Y = \beta0 + \beta1*X*(X <= V) + (\beta1*V + \beta2*(X - V))*(X > V)$, where β0 is intercept; β1 is the slope of the line before the breakpoint, and β2 is the slope of the line after the breakpoint. The terms $(X <= V)$ and $(X > V)$ are Boolean expressions, as in: $(X > V) = 1$ only if X, the ME dietary content, is greater than V, the ME at the breakpoint of the function. $(X > V) = 0$ if X less than V. Similarly, $(X <= V) = 1$ only if X is less than or equal to V and $(X <= V) = 0$ if X is greater than V.

The evaluation parameters used for assessing the model that provided the best fit to the data were R^2, with values closer to 1 meaning a better fit to the data, Akaike's Information Criterion (AIC), and residual sum of squares (RSS). For both AIC and RSS, the model with the lowest values was considered the most adequate (Emiliano et al., 2009; Siqueira et al., 2009).

2.6. Statistical analyses

The assumptions of normality and homoscedasticity (Shapiro-Wilk & Levine) were first tested and met. Growth performance and carcass yield variables were subjected to simple linear (L) and QP regression analyses considering $P < 0.05$. An analysis of variance was performed ($P < 0.05$) to evaluate the behavior of the models with the simple L regression. All statistical procedures were conducted in RStudio for R language (R Core Team, 2015).

3. Results

3.1. Growth performance and carcass and parts yield

The growth performance variables for the growing (21 to 35 d) and finisher (35 to 42 d) periods are presented in Table 2. During all experimental periods, the FI, BWG, FCR, TEI, and EEWG had similar responses; BWG was not influenced by the increasing ME levels, whereas FI, FCR and EEWG showed a linear response ($P < 0.05$). The FI and FCR were linearly decreased with increasing ME levels and EEWG had a linear increase with increasing inclusion of ME. For TEI, a quadratic effect was observed during growing period and linear effect during the finisher period. In the grower period, there was a reduction in ITE in the dietary treatment with 2,950 kcal/kg, but later increased significantly when broiler chickens were fed diets with 3150 and 3,250 kcal/kg. In the finisher period, TEI increased linearly with increasing ME levels. There was no effect of the different dietary ME content on the carcass yield nor parts yield variables (Table 3).

3.2. Determination of optimal ME content for FCR

Recommendations of optimal ME for HRR in the evaluated periods are presented in Table 4. During the grower period, the optimal levels indicated for HRR were 3.264, 3.105 and 3.182 kcal/kg for QP, segmented and LRP regressions, respectively. When evaluating the adjustment of the data, similar results were obtained for R^2 and RSS between the models, differing only for the AIC, because the QP regression presented the lowest value of AIC. In the finisher period, the optimal ME content estimated by the QP, segmented, and LRP models for best FCR were respectively 2814, 2963 and 3,224 kcal/kg. As for the evaluation parameters, similar results were observed among the models for R^2 and RSS, whereas the lowest AIC value was observed in the LRP regression. The behavior of the statistical models was different from the simple linear model in the growing and finisher periods ($P < 0.05$, Figs. 1 and 2).

4. Discussion

4.1. Growth performance and optimal ME content

The ingestion of feed by broiler chickens is regulated by several physiological, environmental, and nutritional factors; among the nutritional factors, the dietary ME content stands out. In the present study, FI was reduced by the increasing energy concentration in the diets, evidencing that broiler chickens can regulate their feed consumption according to the energy intake, and lower or greater FI is expected when energy content is above or below the recommendations, respectively (Barbosa et al., 2008; Gopinger et al., 2017; Nascimento et al., 2011). Similar results were observed by Ferreira et al. (2015) when evaluating six increasing levels of ME (2800, 2900, 3000, 3100, 3200 and 3,300 kcal/kg) in diets for male and female broiler chickens from 1 to 42 d, reporting a reduction on FI when increasing dietary energy. Alvarenga

Table 2
Growth performance of broiler chickens fed different levels of metabolizable energy from 21 to 42 d of age.

Phase (d)	Variable[1]	Metabolizable energy (kcal/kg)					SEM[2]	*P*-value
		2850	2950	3050	3150	3250		
21 to 35	FI (g)[3]	2.33	2.25	2.19	2.16	2.15	15.08	<0.001
	BWG (g)	1.41	1.39	1.40	1.39	1.39	12.08	0.814
	FCR (g:g)[4]	1.67	1.62	1.57	1.54	1.53	0.01	<0.001
	TEI (kcal)[5]	6.64	6.62	6.67	6.81	6.98	46.20	<0.001
	EEWG (kcal:g)[6]	4.74	4.75	4.79	4.85	4.98	0.03	<0.001
35 to 42	FI (g)[7]	1.56	1.49	1.47	1.44	1.40	13.27	<0.001
	BWG (g)	761	735	738	752	746	10.89	0.312
	FCR (g:g)[8]	2.07	2.05	1.99	1.94	1.87	0.02	<0.001
	TEI (kcal)[9]	4.45	4.38	4.49	4.54	4.54	40.36	<0.001
	EEWG (kcal:g)[10]	5.89	6.05	6.16	6.06	6.11	0.07	<0.001

[1] FI: feed intake; BWG: Body weight gain; FCR: Feed conversion ratio; TEI: Total energy intake; EEWG: Energy efficience for weight gain.
[2] Standard error of the mean.
[3] Linear effect ($P = 0.001$): 2348.7 - 44.9x; (R^2: 0.90).
[4] Linear effect ($P = 0.001$) FCR: 1.68 −0.034x; (R^2: 0.94).
[5] Quadratic effect ($P = 0.002$) TEI: 6721.2 - 115.56x + 33.64×[2]; (R^2: 0.99).
[6] Linear effect ($P = 0.003$) EEWG: 4.64 + 0.058x; (R^2: 0.87).
[7] Linear effect ($P = 0.001$) FI: 1583.6 - 37.2x; (R^2: 0.94).
[8] Linear effect ($P = 0.001$) FCR: 2.13 - 0.049x; (R^2: 0.96).
[9] Linear effect ($P = 0.009$) TEI: 4381.4 + 33.6x; (R^2: 0.64).
[10] Linear effect ($P = 0.012$) EEWG: 5.91 + 0.044x; (R^2: 0.48).

Table 3
Carcass and cuts yields of broiler chickens fed increasing levels of metabolizable energy from d 21 to 42.

Variable (%)	Metabolizable energy (kcal/kg)					SEM[1]	*P*-value
	2850	2950	3050	3150	3250		
Carcass	80.99	80.58	80.07	80.84	80.09	0.35	0.184
Breast	34.76	34.66	34.50	34.70	33.71	0.44	0.888
Thigh + Drumstick	28.89	29.08	29.12	29.15	29.28	0.22	0.402
Abdominal fat	1.37	1.42	1.52	1.54	1.48	0.09	0.597

[1] Standard error of the mean.

Table 4
Use of different statistical models to determine optimal metabolizable energy content in broiler chickens diets for optimum feed conversion ratio from d 21 to 42.

Phase (d)	Model[1]	Criteria for data fit[2]			Optimal ME content (kcal/kg)
		AIC	R^2	RSS	
21 to 35	QP	−187.93	0.80	0.03	3264
	Segmented	−185.31	0.80	0.03	3105
	LRP	−187.06	0.80	0.03	3182
35 to 42	QP	−111.40	0.74	0.04	2814
	Segmented	−114.40	0.74	0.04	2963
	LRP	−115.57	0.74	0.04	3224

[1] QP: Quadratic polynomial; LRP: Linear response plateau.
[2] AIC: Akaike Information Criterion; R^2: Coefficient of determination; RSS: Residual sum of squares.

et al. (2011) also observed a reduction in FI when broiler chickens were fed the highest concentration of apparent ME.

Raising ME content in the diet also increased TEI during the evaluated periods, even though a reduction in FI of 182 g and 164 g was observed when increasing energy concentration from the lowest (2850 kcal/kg) to the highest (3250 kcal/kg) levels during the grower and finisher periods, respectively. It was expected that the greater FI recorded for the lower energy diets could equalize TEI compared to the groups fed the higher energy diets, although this might have not occurred due to a physical gastric limitation. The lowest TEI seen with 2,950 kcal/kg may be related to the sharp decrease in FI between 2850 and 2,950 kcal/kg treatments, reduced by 85 and 75 g between phases. Comparing other treatments to the 2,850 kcal group, the reduction of FI was subtler, averaging 32 and 27 g during grower and finisher phases, respectively.

Several studies (Araújo et al., 2005; Moreira et al., 2012; Savoldi et al., 2012; Zhao and Kim, 2017) reported that increasing the energy content of diets favors BWG, but in the current study, no influence of dietary ME on BWG was observed throughout the different phases. Alvarenga et al. (2011), Duarte et al. (2012) and Rodríguez et al. (2016) also found no difference in the BWG of broiler chickens fed with different energy concentrations. This likely implies that the regulation of FI according to ME content helped sustain an adequate BWG.

The EEWG worsened when increasing ME content during both phases. This could be explained by the fact that there was no difference in BWG between treatments, even though TEI was significantly increased with higher inclusion of ME, especially for diets with 3150 and 3,250 kcal/kg. The highest energy contents probably led to an imbalance of energy and protein ratio, leading to a lower supply of amino acids for protein synthesis that diminished the efficiency of lean tissue deposition (Duarte et al., 2007). This could also explain the lack of response in BWG to the high ME diets. Therefore, broiler chickens fed diets with the lowest ME content were perceived as more efficient in utilizing dietary energy, as they used less energy per g of BWG.

Raising the dietary energy content of poultry has been demonstrated to have positive effects on FCR (Dozier et al., 2011). In the current study, FCR was reduced with the increase in energy concentration due to a lower FI, even though higher ME resulted in worse EEWG. Similar results were reported by Abudabos et al. (2014), who assessed increasing energy levels (2925, 2950, 2975 and 3,000 kcal/kg) for broiler chickens from 1 to 35 d of age and correlated the best FCR results to the highest energy levels. Ge et al. (2019) investigated the growth performance of starting broiler chickens fed two energy levels (2940 and 3,030 kcal/kg), showing that a higher energy content reduced FCR.

When determining the appropriate ME content for optimal FCR, it was observed that the indications differed between the statistical models for all the evaluated periods. This outcome was foreseeable due to the different parameters used in each models' equations, despite all using the same database (Pesti et al., 2009). Some models may be more sensitive to data variation, as it is the case for QP model, where the number of levels tested and the location of such levels in the different stages of response (initial, response, stabilization, and toxic) to the increase of a dietary nutrient will directly influence the estimated optimal concentration, usually tending to an overestimation (Euclydes and Rostagno,

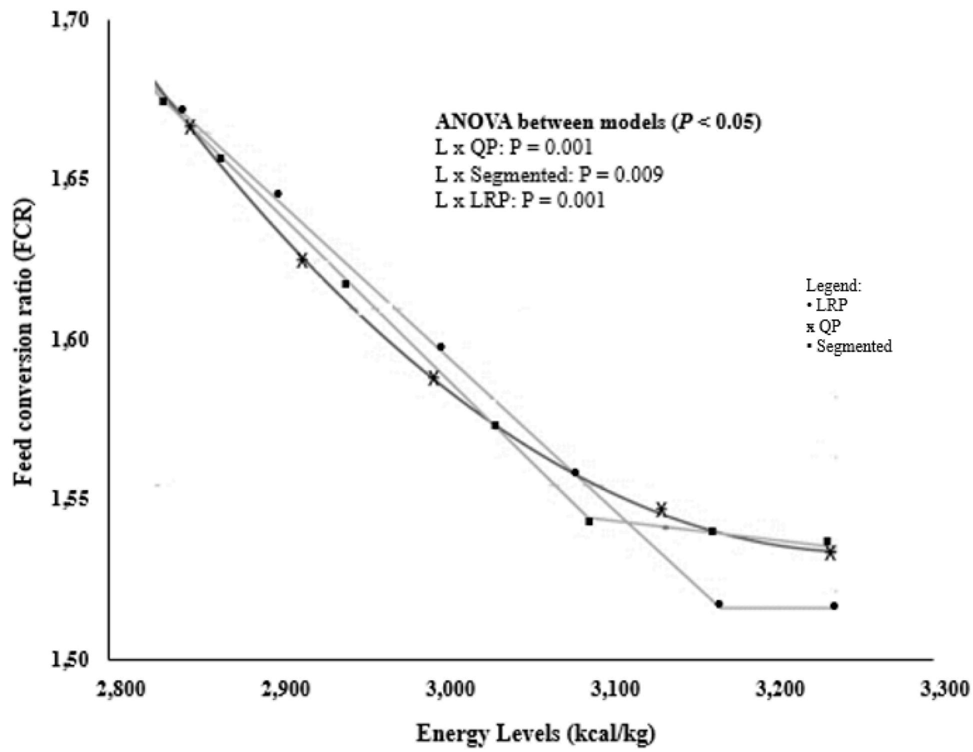

Fig. 1. Response curves of different statistical models for feed conversion ratio of broiler chickens from d 21 to 35. Equations: QP (Quadratic polynomial): 10.04 - 0.005214 * X + (0.000000799) * X^2; Segmented: 3.04 - 0.00048 * X * ($X <= 3105$) - 0.00048 * 3,105 + 0.00043 * (X-3105) * $X > 3105$; LRP (Linear response plateau): 1.52 - 0.000453 * X – 3182, if $X <= 3182$.

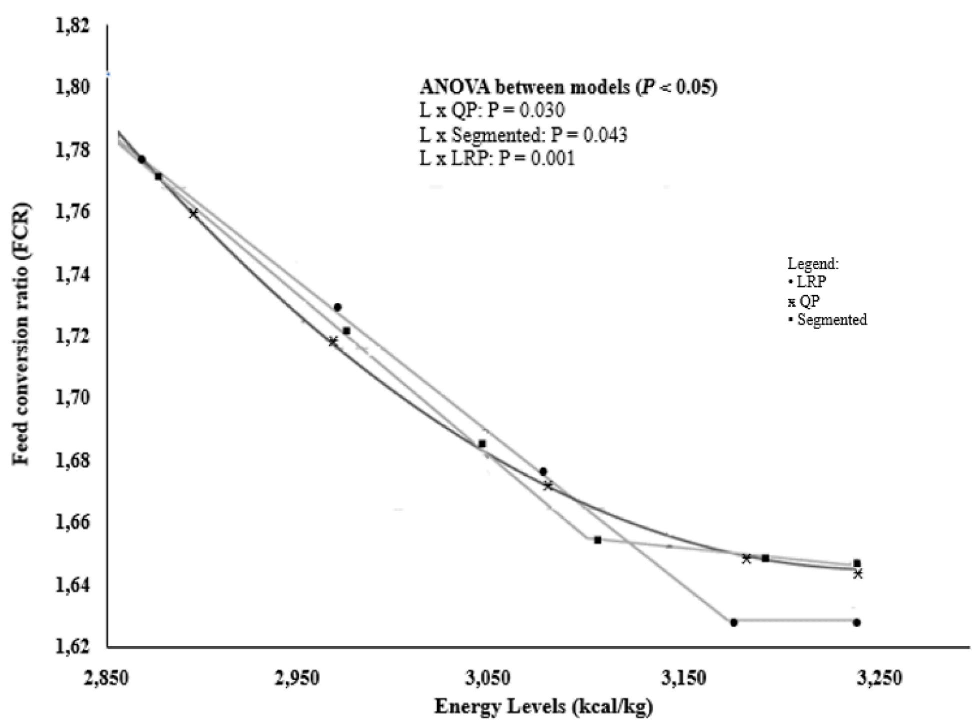

Fig. 2. Response curves of different statistical models for feed conversion ratio of broiler chickens from d 35 to 42. Equations: QP (Quadratic polynomial): 5.84 + 0.005609 * X – 0.000001 * X^2; Segmented: 2.07 – 0.000006 * X * ($X <= 2963$) – 0.000006 * 2963 - 0.00061 * (X - 2963) * $X > 2963$; LRP (Linear response plateau): 1.52 - 0.000453 *(X – 3182), if $X <= 3182$.

2001; Souza et al., 2014). In discontinuous models, such as LRP and segmented, the number of levels has a lesser impact, being mostly influenced by the position of the levels in the different stages of response. The results are more reliable when the concentrations or doses being tested are close to the true requirement, especially during the stages of response and stabilization (Souza et al., 2014).

In this study it was observed that of all statistical models, the QP regression model indicated the highest ME content for FCR in all evaluated phases, reinforcing another one of its characteristics: overestimating optimal concentrations. In the growth phase, the model that best fitted the data was the QP, with the lowest AIC value, although R^2 and RSS were similar among all evaluated models. The optimal ME content predicted by the QP model was 3,264 kcal/kg for an optimal FCR of 1.53. The optimal ME content for maximum performance indicated by the LRP model approached the recommended 3,150 kcal/kg by Rostagno et al. (2017) for average performance male broiler chickens from 22 to 33 d Similarly, Rodríguez et al. (2016) evaluated four ME levels (3040, 3080, 3120, and 3,160 kcal/kg) and reported best FCR in both grower and finisher broiler chickens when feeding 3,120 kcal/kg.

In the finisher period, the established values of R^2 and RSS were similar between all models and only AIC values were distinct: LRP was acknowledged as the best model for this phase because of its lowest AIC, indicating an ME content of 3,224 kcal/kg for optimum FCR of 1.89. This result was very close to that of Rostagno et al. (2017) who recommend a ME content of 3,200 kcal/kg for male broiler chickens of average performance from 34 to 42 d of age.

Feed conversion ratio had a decreasing linear pattern in both phases, so the procedures of each statistical models tested were also compared to the L regression. Unlike other models, the L regression is not recommended when trying to determine optimal nutrient inclusion rates or ingredient doses, as it is characterized by a straight line representing a set of points that follow a single direction - the angle never changes (Martins, 2019), so there are no "break" or "rupture" points, thus it cannot predict an optimal value. All three models (QP, LRP and segmented) were statistically different from the L regression for all phases in this study and hence can be properly used for determining optimal values. The main objective of dose-response studies is to estimate an optimal dose or concentration within the range of values being tested, even when assuming there are innate differences between the statistical models. When using these models to determine the optimal inclusion rate of a diet component, it is primordial to consider the statistical criteria. However, it is equally important to balance the obtained results with biological and economical factors.

4.2. Carcass yield

Increasing dietary ME can provide positive results for growth performance of broiler chickens, but when above the nutritional needs of, it may negatively affect carcass characteristics (Mendes et al., 2004; Meza et al., 2015). In this study, despite the imbalance between amino acids and dietary energy concentration, which could have limited lean tissue growth, carcass and cut yields were not influenced by different ME content, indicating that even greater energy content was not high enough to impact carcass characteristics. It is known that the genetic advancement of commercial broiler chickens increases their energy and nutritional requirements for maximum genetic expression (Gopinger et al., 2017), especially for growth performance and carcass quality traits.

The current study agrees with Meza et al. (2013) who found no difference in carcass, breast, and thigh + drumstick yields when increasing ME dietary levels from 2800 to 3,250 kcal/kg for 21-to-42-D-old broiler chickens. In a more recent study, Meza et al. (2015) investigated increasing energy levels (3000, 3120, 3240, and 3, 360 kcal/kg) along with increasing lysine levels (0.8, 0.9, 1.0, and 1.1%) for 35-to-49-D-old broiler chickens, but still found a lack of effect of different ME on carcass, breast, and thigh + drumstick yields, as well as abdominal fat. Likewise, Abudabos et al. (2014) evaluated four energy levels (2925, 2950, 2975, and 3,000 kcal/kg) in broiler chicken diets and reported no significant differences for breast, thigh + drumstick, and abdominal fat yields at 35 d of age.

5. Conclusion

Increasing ME levels up to 3,250 kcal/kg reduced FI and FCR in both grower and finisher broiler chickens, without affecting carcass yield. The statistical models had different determinations of ME content for optimal FCR according to the production phase. In the grower phase, the QP regression model presented the best fit of the data estimating an optimal dietary concentration of ME of 3,264 kcal/kg, whereas in the finisher phase the LRP model had the best data adjustment, with an estimated 3,224 kcal/kg of ME, making these the recommended concentrations of ME to reduce FCR of grower and finisher broiler chickens.

CRediT authorship contribution statement

F.O. Marx: Investigation, Writing – original draft. **M.V.N. Alvarez:** Formal analysis. **L.S. Bassi:** Writing – review & editing. **A.P. Félix:** Writing – review & editing. **E.L. Krabbe:** Data curation, Conceptualization. **S.G. Oliveira:** Writing – review & editing, Supervision. **A. Maiorka:** Validation, Visualization.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

References

Abudabos, A.M., Saleh, F., Lemme, A., Zakaria, H.A.H., 2014. The relationship between guanidino acetic acid and metabolisable energy level of diets on performance of broiler chickens. Ital. J. Anim. Sci. 13 (3), 3269. https://doi.org/10.4081/ijas.2014.3269.

Alvarenga, R.R., Nagata, A.K., Rodrigues, P.B., Zangeronimo, M.G., Pucci, L.E.A., Hespanhol, R., 2011. Addition of phytase in diets with different levels of metabolizable energy, crude protein and available phosphorus for broilers from 1 to 21 days old. Ci. Anim. Bras. 12, 602–609. https://doi.org/10.5216/cab.v12i4.10247.

Araújo, L.F., Junqueira, O.M., Araújo, C.S.S., Barbosa, L.C.G.S., Ortolan, J.H., Faria, D.E., Stringhini, J.H., 2005. Energy and lysine for broilers from 44 to 55 days of age. Braz. J. Poult. Sci. 7, 237–241. https://doi.org/10.1590/S1516-635X2005000400007.

Barbosa, F.J.V., Lopes, J.B., Figueirêdo, A.V., Abreu, M.L.T., Dourado, L.R.B., Farias, L. A., Pires, J.E.P., 2008. Metabolizable energy levels in diets for broiler maintained in environment of high temperature. R. Bras. Zootec. 37, 849–855. https://doi.org/10.17523/bia.2018.v75.e1420.

Cobb-Vantress, 2013. Cobb 500. Broiler performance & nutrition supplement. https://www.cobb-vantress.com/assets/5a88f2e793/Broiler-Performance-Nutrition-Supplement.pdf.

Dozier, W.A., Gehring, C.K., Corzo, A., Olanrewaju, H.A., 2011. Apparent metabolizable energy needs of male and female broilers from 36 to 47 days of age. Poult. Sci. 90, 804–814. https://doi.org/10.3382/ps.2010-01132.

Duarte, K.F., Junqueira, O.M., Filardi, R.S., Laurentiz, A.C., Souza, H.B.A., Oliveira, T.M. F.S., 2007. Effect of different metabolizable energy levels and feeding programs on performance in broilers lately slaughtered. Acta Sci. Anim. Sci. 29, 39–47. https://doi.org/10.4025/actascianimsci.v29i1.250.

Duarte, K.F., Junqueira, O.M., Borges, L.L., Santos, E.T., Marques, R.H., Quadros, T.C.O., Domingues, C.H.F., 2012. Performance and duodenum morphometry of broiler chickens submitted to different metabolizable energy levels and feed programs at 42 to 57 days of age. Ci. Anim. Bras. 3, 197–204. https://doi.org/10.5216/cab.v13i2.9781 abr./jun.

Emiliano, P.C., Vivanco, M.J.F., Menezes, F.S.M., Avelar, F.G., 2009. Fundamentos e comparação de critérios de informação: akaike and Bayesian. R. Bras. Biom. 27 (3), 394–411.

Euclydes, R.F., Rostagno, H.S., 2001. Estimates of nutritional levels via performance experiments. Poultry and Swine Nutrition. Workshop Latino-Americano Ajinomoto Biolatina, Foz do Iguaçu, PR, pp. 77–88.

Ferreira, G.S., Pinto, M.F., Neto, M.G., Ponsano, E.H.G., Gonçalves, C.A., Bossolani, I.L. C., Pereira, A.G., 2015. Accurate adjustment of energy level in broiler chickens diet for controlling the performance and the lipid composition of meat. Cienc. Rural 45, 104–110. https://doi.org/10.1590/0103-8478cr20130206.

Ge, X.K., Wang, A.A., Ying, Z.X., Zhang, L.G., Su, W.P., Cheng, K., Feng, C.C., Zhou, Y.M., Zhang, L.L., Wang, T., 2019. Effects of diets with different energy and bile acids levels on growth performance and lipid metabolism in broilers. Poult. Sci. 98, 887–895. https://doi.org/10.3382/ps/pey434.

Gries, D., Schneider, F.B., 1993. Chapter 2. Boolean Expressions", A Logical Approach to Discrete Math, Texts and Monographs in Computer Science. Cornell University Upson Hall, Ithaca, NY, US.

Gopinger, E., Krabbe, E.L., Surek, D., Lopes, L.S., Avila, V.S., 2017. Live performance, carcass, and bone quality responses of growth and finisher broilers to dietary metabolizable energy levels. Braz. J. Poult. Sci. 19, 559–566. https://doi.org/10.1590/1806-9061-2017-0508.

Martins, M.E.G., 2019. Simple linear regression. R. Cienc. Elem. 7, 3. https://doi.org/10.24927/rce2019.045.

Mello, H.H.C., Gomes, P.C., Rostagno, H.S., Albino, L.F.T., Souza, R.M., Calderano, A.A., 2009. Metabolizable energy values of feedstuffs obtained from poultry at different ages. R. Bras. Zootec. 38, 863–868. https://doi.org/10.1590/S1516-35982009000500012.

Mendes, A.A., Moreira, J., Oliveira, E.G., Garcia, E.A., Almeida, M.I.M., Garcia, R.G., 2004. Effect of dietary energy on performance, carcass yield and abdominal fat of broiler chickens. R. Bras. Zootec. 33, 2300–2307. https://doi.org/10.1590/S1516-35982004000900016.

Meza, S.K.L., Nunes, R.V., Tsutsumi, C.Y., Scherer, C., Savoldi, T.L., 2013. Effect of metabolizable energy and digestible lysine levels on 42-day-old broiler carcass yield. Scient. Agrar. Paran. 12, 420–424. https://doi.org/10.18188/1983-1471/sap.v12nsupp420-424.

Meza, S.K.L., Nunes, R.V., Tsutsumi, C.Y., Vieites, F.M., Scherer, C., Henz, J.R., Silva, I. M., Bayerle, D.F., 2015. Metabolizable energy and digestible lysine levels on the composition and carcass yield of broilers. Semin. Cienc. Agrar. 36, 1079–1090. https://doi.org/10.5433/1679-0359.2015v36n2p1079.

Moreira, A.S., Santos, M.S.V., Vieira, S.S., Tavares, F.B., Manno, M.C., 2012. Performance of broiler chickens fed diets containing different levels of metabolizable energy. Arq. Bras. Med. Vet. Zootec. 64, 1009–1016. https://doi.org/10.1590/S0102-09352012000400030.

Nascimento, G.A.J., Rodrigues, P.B., Freitas, R.T.F., Reis Neto, R.V., Lima, R.R., Allaman, I.B., 2011. Prediction equations to estimate metabolizable energy values of energetic concentrate feedstuffs for poultry by the meta-analysis process. Arq. Bras. Med. Vet. Zootec. 63, 222–230. https://doi.org/10.1590/S0102-09352011000100032.

Nunes, C.C.F., Morais, A.R., Muniz, J.A., Sáfadi, T., 2004. Variances of the critical point of a quadratic regression equation. Ciênc. Agrotec. 28, 389–396. https://doi.org/10.1590/S1413-70542004000200020.

Nunes, R.V., Schneider, S.E., Souza, C., Sangali, C.P., Polese, C., Bueno, R.S., Vieites, F. M., 2015. Digestible lysine requirement for laying hens from 50 to 66 weeks of age. Arq. Bras. Med. Vet. Zootec. 67, 1675–1683. https://doi.org/10.1590/1678-4162-7810.

Oviedo-Rondón, E.O., Waldroup, P.W., 2002. Models to estimate amino acid requirements for broiler chickens: a review. Int. J. Poult. Sci. 5, 106–113. https://doi.org/10.3923/ijps.2002.106.113.

Pack, M., Hoehler, D., Lemme, A., 2003. Economic assessment of amino acid responses in growing poultry. In: D'MELLO, J.P.F. (Ed.), Amino Acids in Animal Nutrition. Cambridge: CABI Publishing, Edinburgh, UK.

Pesti, G.M., Vedenov, D., Cason, J.A., Billard, L., 2009. A comparison of methods to estimate nutritional requirements from experimental data. Brit. Poult. Sci. 50, 16–32. https://doi.org/10.1080/00071660802530639.

Pompeu, M.A., Baião, N.C., Lara, L.J.C., Ecco, R., Rocha, J.S.R., Fernandes, M.N.S., Barbosa, V.M., Miranda, D.J.A., 2013. Choline supplementation in diets for male broilers in the growing phase. Arq. Bras. Med. Vet. Zootec. 65, 1836–1842. https://doi.org/10.1590/S0102-09352013000600035.

Portz, L., Dias, C.T.S., Cyrino, J.E.P., 2000. A broken-line model to fit fish nutrition requirements. Scient. Agric. 57, 601–607. https://doi.org/10.1590/S0103-90162000000400002.

R Core Team, 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Rodríguez, F.I., Chavira, J.S., Gómez, M.F.M., Nunez, O.M.M., Vizcarra, V.M.G., Florentino, O.F.G., León, J.A.R., 2016. Effect of diets with different energy concentrations on growth performance, carcass characteristics and meat chemical composition of broiler chickens in dry tropics. SpringerPlus 5, 1937. https://doi.org/10.1186/s40064-016-3608-0.

Rostagno, H.,.S., Albino, L.F.T., Hannas, M.I., Donzele, J.L., Oliveira, R.F., Barreto, S.L. T., Sakomura, N.K., Perazzo, F.G., Saraiva, A., Teixeira, M.L., Rodrigues, P.B., Brito, C.O., 2017. Tabelas Brasileiras para Aves e Suínos – Composição de Alimentos e Exigências Nutricionais. Universidade Federal de Viçosa, Viçosa, MG, Brazil.

Sakomura, N.K., Rostagno, H.S., 2007. Métodos De Pesquisa Em Nutrição De Monogástricos. FUNEP Jaboticabal, SP, Brazil.

Savoldi, T.L., Nunes, R.V., Scherer, C., Tsutsumi, C.Y., Scheneiders, J.L., Marques, M.F. G., Schone, R.A., Meza, S.K.L., 2012. Levels of metabolizable energy and digestible lysine for performance in broiler chicks from 1 to 10 days of age. Scient. Agrar. Paran. 11, 49–58. https://doi.org/10.18188/sap.v11i0.7870.

Siqueira, J.C., Sakomura, N.K., Nascimento, D.C.N., Fernandes, J.B.K., 2009. Mathematical models to estimate digestible lysine of ISA Label broilers. R. Bras. Zootec. 38, 1732–1737. https://doi.org/10.1590/S1516-35982009000900013.

Souza, F.A., Malheiros, E.B., Carneiro, P.R.O., 2014. Positioning and number of nutritional levels in dose-response trials to estimate the optimal-level and the adjustment of the models. Cienc. Rural 44, 1204–1209.

Zhao, P.Y., Kim, I.H., 2017. Effect of diets with different energy and lysophospholipids levels on performance, nutrient metabolism, and body composition in broilers. Poult. Sci. 96, 1341–1347. https://doi.org/10.3382/ps/pew469.