Effects of dietary energy and protein levels on growth curve parameters of Khazak native chickens

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Effects of dietary energy and protein levels on growth curve parameters of Khazak native chickens

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Abstract

This study was conducted to evaluate the effect of dietary energy (ME) and protein (CP) on growth parameters and absolute growth rates in the different ages of the Khazak chicks. A total of 360 one-day-old Khazak chicks were obtained from a local hatchery and in a 3×3 factorial experiment with completely randomized design, chicks were randomly allocated to experimental diets including 2,600, 2,800, and 3,000 kcal of ME/kg, and each containing 17, 19, and 21% CP from 7 to 98 days of age. Four growth model (Gompertz, Logistic, Lopez, and Richards) were fitted on weekly body weight data and the best model were selected by the goodness of fit criteria. Growth curve parameters were predicted for all chicks using the best model and other parameters including age (T_i) and weight (W_i) at the inflection point and absolute growth rate (AGR) in different ages were calculated from growth curve parameters. All parameters were analyzed using the general linear model procedure of SAS. Based on goodness of fit criteria, the Richards model had the lowest Akaike's Information Criteria (AIC), root mean square error (RMSE), and highest adjusted determination coefficient (R^2_{Adj}) than other models and was selected as the best model. The effect of ME was significant on the mature index (k), W_i, T_i, and all AGR parameters ($P<0.05$) while CP levels were significant on final weight (W_f), W_i, and AGR parameters ($P<0.05$). The chicks fed with a diet containing 2,600 kcal of ME/kg and 17 % CP had the higher k parameter, and lower W_i, T_i, and AGR than those fed with other diets ($P<0.05$). Considering that the level of 2,800 kcal of ME/kg and 19 % CP had no significant difference with the level of 3,000 kcal of ME/kg and 21 % CP, therefore diet with 2,800 kcal of ME/kg and 19 % CP was suggested as optimum levels for change the growth curve parameter and having best performance for Khazak chickens during 7 to 98 days of old.

Keywords: Inflection point, growth rate, mathematical model, native chicken.

Highlights

- Studies on long-term growth curves of animals can be helpful in the dynamically understanding of growth patterns and responses to dietary nutrient density as well.
- Improvement of the growth performance for native chickens in terms of growth by demining appropriate levels of energy and protein could be useful.
- The effect of dietary energy was significant on the mature index (k), age (T_i) and weigh (W_i) at the inflection point, and absolute growth rate (AGR) while protein levels were significant on final weight, W_i and AGR parameters ($P<0.05$).

1. Introduction

In rural areas of the tropical, rearing native poultry plays a pivotal role in the production of high-quality animal protein resources with organic properties and income generation (Norris et al 2007; Padhi, 2016). Recently, public concern was increased about the use of modern broiler genotypes for the production of chicken meat, and the tendency toward the consumption of meat that produced from slow-growing broilers instead of fast-growing is increasing (Dyubele et al., 2010). Furthermore, meat produced by modern broiler genotypes is less palatable than native breeds (Wattanachant, 2008). Rural poultry has significant prospects for future development due to the easy and abundant availability of all necessities input including land, labor, and feed resources in rural areas. This section can help in increasing household income and improving family health through best nutrition (Shehbaz Anjum and Hassan Khan, 2008).

Knowledge of bird requirements to access their maximum production capacity is one of the solutions to increasing poultry production in the countries. It is very important to consider the main components of feed due to the high cost of feed in poultry production farms (Wijtten et al., 2004). Energy and protein are the main nutrients in most livestock diets that allotted about 90% of the total feed cost. Therefore, these nutrients must be used most efficiently for the formulation of poultry rations and the profitability of production (Durunna et al., 2005). There is little information about nutritional improvement in native breed than commercial broiler chickens. In this regard, determining the optimal energy and protein levels of the diet is very important to maximize the production parameters and carcass characteristics of native chickens (Miah et al., 2014). In some studies, the effect of different levels of energy and protein on growth performance in Korat (Maliwan et al., 2019), Venaraja (Perween et al., 2016), Desi (Miah et al., 2014), Arabi (Al-Khalifa and Al-Nasser, 2012), Assel (Haunshi et al., 2012) Betong (Nguyen et al., 2010), chickens were reported. However, in these studies, the effect of energy and protein was investigated on body weight gain, feed intake, and feed conversion ratio.

The growth of an animal can be defined as any change in body size per time (Narinc et al., 2017). These changes can be measured as body weight in regular intervals and summarized by mathematical models fitted to growth curves (Aggrey, 2002). Growth curves in animals are generally S-shaped Growth curves and can be divided into two phases including the accelerated phase (the growth from hatching to the inflection point) and decelerating phase (the growth rate decreased until to a mature weight) (Selvaggi et al., 2015). The mathematical models that are used to describe growth curves have biological parameters such as body weight at a specific time, body weight at maturity, age and weight at the inflection point, growth rate (Masoudi and Azarfar, 2017). The growth curve can be useful in describing the production of animals, especially when they can be estimated using the number of daily feed requirements (Abbas et al., 2014). It has been shown that the shape of the growth curve was affected by the composition of the diet (Mohammad, 2015). Prediction of production, as well as the nutritional requirements of birds of different ages, can result in a restriction on the level of ad libitum access to feed (Lopez et al., 2000).

Studies on long-term growth curves of animals can be helpful in the dynamically understanding of growth patterns and responses to dietary nutrient density as well (Russo, 2009, Yun et al., 2015). In a study by Nahashon et al. (2010) reported that dietary protein and energy affect the growth parameters of the French guinea fowl by using of Gompertz-Laired model. Growth curve parameters of commercial broiler and native chickens that fed by different energy levels by four growth models were studied and a significant effect of energy level was reported on some growth parameters (Moharrery and Mirzaei, 2014.).

The Khazak breed is one of the small native breeds in the Sistan (Sistan region, IRAN), with short legs relatively high potential for egg production. A tendency toward the native chicken consumption in this region was more than industrial chickens, so an improvement of the performance for this breed in terms of growth by demining appropriate levels of energy and protein could be useful (Faraji-Arough et al., 2019). Therefore, this study aimed to evaluate the growth curve parameters of Khazak chickens fed diets containing different levels of energy and protein.

2. Materials and methods

2.1. Experiment design and bird management

The present study was performed in an experiment poultry farm of the Research Center of Domestic Animals (RCDA) in the University of Zabol, Zabol, Iran. Animal handling and experimental procedures of the study were conducted following approved guidelines of the Research Animal Committee of the Research Institute at the University of Zabol. A total of 360 one-day-old Khazak chicks were wing-banded and weighed individually. Chicks were raised together until 7 days of age in floor pens containing litter composed of wood shaving. At one week of age, chicks were weighed and randomly distributed into nine groups. Each group had 40 chicks that were allocated into 4 replicate with 10 birds in each. The chicks were fed with a maize-soybean meal-based diet supplying three levels of metabolizable energy (2,600, 2,800, and 3,000 kcal/kg) and three levels of crude protein (17%, 19%, and 21%) in a 3×3 factorial experiment with a completely randomized design (Table 1). Feed and water were provided ad libitum during the experiment (7 to 98 days of age). A brooding temperature was maintained at 35 °C from day 1 to 7 and then gradually reduced 2 °C per week until 21 °C. The chicks were individually weighed weekly until the 14th week of age.

Table 1.

2.2. Mathematical models

Four non-linear mathematical models including Gompertz, Logistic, Lopez, and Richards were fitted to the body weight data to recognize the best model. The age and weight at the inflection point and Absolute growth weight in different ages for each model were calculated based on the model parameters. The equations of fitted models and biological parameters are shown in Table 2. In all models, W is the body weight of a bird at age t, W_0, W_f, and k are initial and final weights, and coefficient of relative growth or maturing index, respectively. The parameter b indicates the age at approximately half the maximum body weight, and m represents the shape parameter. The fitting of models on body weight data was performed by nlme package of R software (Pinheiro et al. 2014).

Table 2.

After fitting the models, four goodness of fit criteria were used to compare the models and selection of the best model for studied populations (Teleken et al., 2017):

1) Adjusted determination coefficient (R^2_{Adj}):

$$R^2_{Adj} = 1 - \left[\left(\frac{n-1}{n-k}\right) * (1 - R^2_{model})\right]$$

2) Akaike’s Information Criteria (AIC) = nln(SSE/n)+2k

3) Bayesian Information Criterion (BIC) = n.ln(SSE/n) +k.ln(n)

4) Root mean square error (RMSE):

$$RMSE = \sqrt{\frac{SSE}{n-k}}$$

where n and k are the number of observation and parameters, respectively, and R^2_{model} is determination coefficient that is equal to 1-(SSE/SST). SSE and SST represent the sum of square errors and total sum of squares, respectively. Smaller value for AIC, BIC, RMSE and the highest value for R^2_{Adj} a model indicate the best model.

The parameters of the model for each bird were obtained by the nlsList package of R software using the best model. Then age and weight at the inflection point and absolute growth rate in different ages for each bird have calculated as the model parameters.

2.3. Statistical analysis

Data were analyzed using the general linear model procedure of SAS (SAS Institute, 2008). A two-way ANOVA was performed to test the main effects of different levels of energy and protein and their interaction effects on model parameters, age (T_i) and weight (W_i) at the inflection point, and absolute growth rate at ages 14, 21, 28, 35,42, 49, 56, 63, 70, 77, 84, 91 and 98 days of age. The differences among treatment means were compared by Tukey’s test procedure and means considered significant when $P<0.05$.

3. Results

The mean and standard error of growth parameters for studied models for all populations is shown in table 3. Logistic and Lopez models overestimated W_0 and W_f parameters than other models, respectively. The highest and lowest value of the k parameter was estimated by Lopez and Gompertz models, respectively. The values of age (T_i) and weight (W_i) at the inflection point in the Lopez model were lower than other models despite having higher W_f and k parameters. However, the highest value for mentioned parameter was estimated by the Logistic model (56.965 days and 447.600g, respectively). Regarding the goodness of fit criteria, four models were fitted on body weight data and are suitable to describe the growth curve of this population. However, the smallest AIC and RMSE were calculated for the Richards model among all models, and the value R^2_{Adj} for Richards was higher than other models. Therefore, the Richards model was selected as the best model to describe the growth curve in this study, and the effect of different levels of energy and protein on growth curve parameters were evaluated with this model.

Table 3.

The mean growth curve parameters and absolute growth rate in different ages for ME and CP levels are presented in Table 4. The initial body weight (W0) was high in birds fed a diet containing 3000 kcal of ME /kg than other levels of ME, but the difference between ME levels was not significant ($P>0.05$). A similar trend was observed for final body weight (W_f) so that the final body weight was high in higher levels of ME ($P>0.05$). However, the predicted maturing index (k) was significantly lower ($P<0.05$) in birds fed with a diet containing 3000 kcal of ME/kg compared with those fed the 2600 and 2800 kcal of ME/ kg diets.

Table 4.

The difference between shape parameter (m) among dietary ME levels was not significant ($P>0.05$), but the difference of age (T_i) and weight (W_i) at the inflection point among ME levels were significant ($P<0.05$) so that birds fed with a diet containing 3000 kcal of ME /kg arrived at age at the inflection point in higher ages than other ME levels. Forasmuch as the birds fed with higher levels (3000 and 2800 kcal/kg) of ME had a higher Ti so these birds showed a higher weight at the inflection point (W_i) than those fed diet containing 2600 kcal of ME/kg ($P<0.05$). The effect of diet CP levels was significant on W_f and W_i parameters were significant ($P<0.05$, Table 4) so that the final weight and weight at the inflection point of birds fed with a diet containing 21 and 19 % CP was higher than those fed with the 17 % CP diet. Although, diets containing high CP had higher W0, m, and Ti values and lower k values than other diets, the difference between CP levels was not significant ($P>0.05$).

The mean absolute growth rate in different ages for various levels of ME and CP are presented in Table 4. The effect of ME and CP levels was significant on absolute growth rate in different ages ($P>0.05$). The highest absolute growth rate was observed for birds fed a diet containing 3000 kcal of ME/kg and 21 % CP, while the lowest absolute growth rate was related to the diet containing 2600 kcal of ME/kg and 17 % CP. However, the mean absolute growth rate for birds that received a diet with 2800 kcal of ME/kg and 19 % CP was not significant with a high level of energy (3000 kcal/kg) and protein (21 %).

Table 5 shows the interaction effect of ME and CP on growth curve parameters and Absolute growth rate in different ages. The interaction effect of ME and CP was significant on the k and W_i parameters ($P<0.05$) and the differences of W_0, W_f, m, and T_i were not significant ($P>0.05$). The mean of the mature index (k) for birds fed with a diet containing 2600 kcal of ME/kg and 16 % CP was higher than other treatments, but only its difference was significant than diets with 3000 kcal of ME/ kg and 19 and 21 % CP. The highest value of weight at the inflection point was birds fed with a diet containing 3000 kcal of ME/kg and 21 % CP that was significantly higher than the 2600 kcal of ME/kg and 17 % CP diet. Interaction of ME and CP had a significant effect on absolute growth rate in different ages except for absolute growth rate at 77 and 98 days of age ($P<0.05$). In all ages, the mean absolute growth rate for birds fed with a diet containing 2600 kcal of ME/kg and 17 % CP was lower than other diets.

Table 5.

4. Discussion

Mathematical models are used for describing the growth curve, have the main role in poultry improvement programs. The importance of these models and use of models in poultry have been reported in other studies (Anthony et al., 1991; Aggrey, 2002) especially when the growth is related to the nutritional components (Aggrey, 2004). Cumulative feed consumption until slaughter weight in poultry depends on growth rate and the shape of the growth curve, therefore the use of a mathematical model in combination with feed intake data can be useful in bioeconomic studies (Pasternak and Shalev, 1983).

In this study, the Richards model was selected as the best model to describe the growth curve of Khazak chickens. In agreement with this finding, the superiority of the Richards models to describe the growth curve of broiler and native chickens that fed with different levels of ME was reported (Tompic et al., 2011; Moharrery and Mirzaei, 2014).

Overestimation of W_0 parameter with Logistic model and k, W_f parameters with Lopez model was reported in a study of the growth curve in broiler chickens (Moharrery and Mirzaei, 2014; Masoudi and Azarfar, 2017; Faraji-Arough et al., 2019) which was in agreement with our results. In growth curve studies in native chickens, various models were introduced as the best model to describe the growth curve. The Gompertz model for Nigerian native chickens (Adenaike et al., 2017), slow-growing chickens in China (Zhao et al., 2015), Poland medium-growing chickens (Michalczuk et al., 2016), Logistic model for slow-growing chickens in the organic system (Eleroglu et al., 2014), Von Bertalanffy for Korean native chickens (Manjula et al., 2016), and Lopez for Khazak chickens (Faraji-Arough et al., 2019) was reported. Although, Faraji-Arough et al. (2019) introduced the Lopez model for Khazak chickens that in contrast with present results. However, the data of body weight in this study was related to chicks that fed with diets with different levels of ME and CP, but the used data in a study by Faraji-Arough et al. (2019) was collected from chicks that used the same diet (2,800 kcal of ME/ kg and 16% CP) that could a reason for this difference.

Our findings indicates that the maturity index (k) decreased linearly with increasing of ME and CP levels (Table 4) whereas the final weight (W_f) increased with the increment of ME and CP levels. Inverse association between W_f and k parameter was reported in other studies (Adenaike et al., 2017; Faraji-Arough et al., 2019) which indicate early maturing in birds result in the slow rate of growth in the first weeks of age. Furthermore, a correlation between W_f and k was reported negative (>-0.90, Masoudi and Azarfar, 2017; Faraji-Arough et al., 2019), therefore the chicks with a lower k value will have a higher W_f.

Although, the effect of different levels of ME and CP on growth performance of native chickens was reported in some studies (Nguyen et al., 2010; Haunshi et al., 2012; Al-Khalifa and Al-Nasser, 2012; Miah et al., 2014; Perween et al., 2016; Maliwan et al., 2019). However, in these studies, growth performance was considered as body weight gain, feed intake, and feed conversion ratio.

In a study on broiler chickens, some of the growth curve parameters especially W_f, W_i, growth rate on days 28, 35, and 42 were significantly affected by different levels of corn bran of diet (Masoudi and Azarfar, 2018).

Effect of ME and CP on growth curve parameter of French guinea fowl by Gompertz model was studied by Nahashon et al. (2010) and no significant effect of ME on growth curve parameter except for W_0 was reported that was contrary to the results of the present study, but similar to our result, the effect of CP was significant on W_i and growth rate. It has also been reported that the final body weight of guinea fowl broiler fed diet containing 3,100 or 3,150 kcal of ME /kg was significantly higher than those fed the 3,050 kcal of ME /kg diet (Nahashon et al., 2005) that was opposite with our finding.

Based on the Richards model, the decreased dietary ME concentration cause a linear decrease in W_f in broiler chickens ($P<0.05$) (Moharrery and Mirzaei, 2014) but no effect of ME on W_f and other growth parameters in native chickens was reported that was similar with present results. Adaptation of native chickens in consuming feed of lower ME concentration can be a reason for the lack of significant effect of dietary ME on W_f. On the other hand, the native chickens do not need high energy concentration in their feed due to having a slower growth rate and small size at maturity. Therefore, their feed intake was reduced with increasing ME in diet, which can be another reason for the non-significant effect of ME on W_f (Moharrery and Mirzaei, 2014).

After hatch, the growth of birds is accelerated till a certain age which this time showed by age at the inflection point (T_i) and growth rate of bird in this maximum in this phase. The growth of birds decreased gradually after this age to achieve their mature weight (Sakomura and Rostagno, 2016). Our finding shows that this age for chicks fed with a diet containing a high level of ME significantly increased than a low level of ME. The increase of T_i provides an opportunity for the chicks to gain more body weight (W_i). Similar to the present results, a significant effect of ME and CP on the growth curve parameter of Broiler chickens by Logistic and Gompertz was reported (Koushandeh et al., 2019). An increasing trend of W_i, T_i, and absolute growth rate and decreasing trend of k parameter was reported with increasing the dietary CP level in gibel crap (Yun et al., 2015) that was similar with the present result.

5. Conclusion

Based on goodness of fit criteria, the Richards model was the best model to describe the growth curve of Khazak chicks fed with a diet containing different levels of ME and CP. The ME and CP levels and their interaction had a significant effect on W_i and absolute growth rate in different ages. Also, the k and T_i parameter was affected significantly by ME levels and the final weight (W_f) of chicks fed with a diet containing a high level of CP was significantly higher than those fed with a low level of CP diet. The difference of many studied parameters was not significant between 2,800 and 3,000 kcal of ME /kg and 19 with 21 % CP, thus diet with 2,800 kcal of ME /kg and 19% CP can be suggested for Khazak chickens during 7 to 98 days of age to the optimum improvement of the growth curve. On other hand, the results of this study can be useful in nutritional management and can help the producer to formulate the best diet when the growth rate is at its maximum.

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Declarations

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Conflict of Interest

The authors declare that there is no conflict of interest.

Ethics approval

This article does not contain any studies with human participants performed by any of the authors. Animal handling and experimental procedures of the study were conducted following approved guidelines of the Research Animal Committee of the Research Institute at the University of Zabol.

Consent to participate

All authors agree on their participation in the work herein reported.

Consent for publication

All authors confirm to publish the manuscript in Tropical Animal Health and Production.

Availability of data

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Authors' contributions

Hadi Faraji-Arough: Conceptualization, Methodology, Formal analysis, Supervision, Visualization, Writing - review & editing, Project administration, funding acquisition. **Mahmoud Ghazaghi**: Data curation, Validation, Investigation, Visualization, Writing - original draft preparation. **Farzad Bagherzadeh Kasmani**: Data curation, Investigation, Formal analysis, Visualization, Writing -review & editing. **Mohammad Rokouei**: Conceptualization, Methodology, software, Investigation, Visualization, Writing - review & editing.

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Table 1 Ingredients and nutrient composition of the experimental diets

Item	**Diets**								
Ingredient	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Corn grain	57.92	55.36	52.81	66.87	64.31	61.82	73.79	67.66	61.43
Soybean meal (44% CP)	18.07	23.45	28.87	19.76	25.15	30.64	21.29	26.54	31.80
Wheat bran	19.46	16.94	14.29	8.87	6.35	3.43	-	-	-
Dicalcium phosphate	1.64	1.62	1.60	1.75	1.73	1.72	1.84	1.80	1.76
Calcium CO3	1.47	1.45	1.43	1.43	1.41	1.39	1.40	1.38	1.37
Sodium bicarbonate	0.54	0.32	0.17	0.41	0.19	0.17	0.30	0.18	0.17
NaCl	0.29	0.29	0.29	0.30	0.30	0.30	0.21	0.30	0.30
Trace mineral premix[1]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Vitamin premix[2]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
DL- Methionine	0.11	0.06	0.05	0.10	0.06	0.03	0.10	0.05	0.03
Oil	-	-	-	-	-	-	0.57	1.59	2.63
Calculated chemical composition									
Metabolizable energy (kcal/kg)	2600	2600	2600	2800	2800	2800	3000	3000	3000
Crude protein (%)	17.00	19.00	21.00	17.00	19.00	21.00	17.00	19.00	21.00
Lysine (%)	0.78	0.91	1.05	0.79	0.92	1.06	0.79	0.93	1.07
Methionine (%)	0.33	0.35	0.36	0.33	0.35	0.35	0.33	0.35	0.35
Methionine + cysteine (%)	0.62	0.63	0.66	0.62	0.63	0.66	0.62	0.63	0.65
Calcium (%)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Available phosphorus (%)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

[1] Vitamin premix provided per kilogram of diet: vitamin A (from vitamin A acetate), 11,500 U; cholecalciferol, 2,100 U; vitamin E (from dl-α-tocopheryl acetate), 22 U; vitamin B_{12}, 0.60 mg; riboflavin, 4.4 mg; nicotinamide, 40 mg; calcium pantothenate, 35 mg; menadione (from menadione dimethyl-pyrimidinol), 1.50 mg; folic acid, 0.80 mg; thiamine, 3 mg; pyridoxine, 10 mg; biotin, 1 mg; choline chloride, 560 mg; ethoxyquin, 125 mg.

[2] Mineral premix provided per kilogram of diet: Mn (from MnSO4·H2O), 65 mg; Zn (from ZnO), 55 mg; Fe (from FeSO4·7H2O), 50 mg; Cu (from CuSO4·5H2O), 8 mg; I (from Ca $(IO_3)2\cdot H_2O$), 1.8 mg; Se, 0.30 mg; Co (from Co_2O_3), 0.20 mg; Mo, 0.16 mg.

[3] DEB: Dietary electrolyte balance represents dietary Na + K – Cl in mEq/kg of diet.

Table 2 Equation of mathematical models and biological parameters

Model	Equation	T_i	W_i	Absolute growth rate
Gompertz	$\mathrm{W} = \mathrm{W_0} \exp\left\{[1 - \exp(-\mathrm{k} \times \mathrm{t})] \ln\left(\frac{\mathrm{W_f}}{\mathrm{W_0}}\right)\right\}$	$\frac{1}{\mathrm{k}}\left[\ln\left(\ln\left(\frac{\mathrm{W_f}}{\mathrm{W_0}}\right)\right)\right]$	$\frac{\mathrm{W_f}}{\mathrm{e}}$	$kWln\left(\frac{W_f}{W}\right)$
Richards	$\mathrm{W} = \frac{\mathrm{W_0 W_f}}{[\mathrm{W_0^m} + (\mathrm{W_f^m} - \mathrm{W_0^m})\mathrm{e^{-kt}}]^{1/\mathrm{m}}}$	$\frac{1}{\mathrm{k}} \times \ln\left(\frac{\mathrm{m}}{(\mathrm{W_f^m} - \mathrm{W_0^m})/\mathrm{W_0^m}}\right)$	$\frac{\mathrm{W_f}}{\sqrt[\mathrm{m}]{\mathrm{m} + 1}}$	$kW\left(\frac{W_f^m - W^m}{mW_f^m}\right)$
Logistic	$\mathrm{W} = \frac{\mathrm{W_0 W_f}}{[\mathrm{W_0} + (\mathrm{W_f} - \mathrm{W_0})\exp(-\mathrm{k} \times \mathrm{t})]}$	$\frac{1}{\mathrm{k}} \ln\left(\frac{\mathrm{W_f} - \mathrm{W_0}}{\mathrm{W_0}}\right)$	$\frac{\mathrm{W_f}}{2}$	$kW\left(1 - \frac{W_f}{W}\right)$
Lopez	$\mathrm{W} = \frac{(\mathrm{W_0} \times \mathrm{b^k}) + (\mathrm{W_f} \times \mathrm{t^k})}{(\mathrm{b^k} + \mathrm{t^k})}$	$\mathrm{b}\left(\frac{\mathrm{k} - 1}{\mathrm{k} + 1}\right)^{1/2}$	$\frac{\left[\left(1 + \frac{1}{\mathrm{k}}\right)\mathrm{W_0} + \left(1 - \frac{1}{\mathrm{k}}\right)\mathrm{W_f}\right]}{2}$	$k\left(\frac{t^{k-1}}{b^k + t^k}\right)(W_f - W)$

W in all models is the body weight of bird at age t, W_0, W_f and k are initial and final weights, and coefficient of relative growth or maturing index, respectively. The parameter b is the age at approximately half maximum body weight, and m represents the shape parameter.

Table 3 Estimated parameters and goodness of fit criteria for each model

Parameter*	**Gompertz**	**Logistic**	**Lopez**	**Richards**
W_0±SE	32.198±2.254	51.740±2.024	45.190±4.813	38.580±3.803
W_f±SE	1145.270±29.826	895.200±11.640	1520.000±117.200	1032.000±5.029
k±SE	0.024±0.0007	0.049±0.0010	1.891±0.085	0.031±0.004
m±SE	-	-	-	0.270±0.143
b±SE	-	-	94.100±7.469	-
W_i	421.321	447.600	392.640	425.816
T_i	53.041	56.965	50.498	53.745
RMSE	86.538	86.755	86.767	86.497
AIC	31319.37	31332.69	31332.56	31317.83
BIC	31342.92	31356.24	31361.99	31343.26
R^2_{Adj}	89.822	89.771	89.775	89.832

* W_0 (g), W_f (g), k (g per d), m and b (d) are initial weight, final (mature weight) weight, coefficient of relative growth or maturing index, the shape parameter, and the age at approximately half maximum body weight, respectively. SE: Standard error; W_i; weight at the inflection point (g); T_i; Age at the inflection point (d); RSME: Root mean square error; BIC: Bayesian information criterion; AIC: Akaike information criterion and R^2_{Adj}; adjusted coefficient of determination.

Table 4 Effect of energy and protein levels on growth curve parameters and Absolute growth rate in different ages

Trait	**ME(k cal/kg)**			**P value**	**CP (%)**			**P value**	**ME*CP**	**SEM**
	2600	2800	3000		17	19	21		P value	
W_0	38.745	39.297	40.894	0.6577	39.175	38.856	40.906	0.6641	0.9422	13.338
W_f	1070.95	1156.59	1193.28	0.1107	1043.26^{b}	1156.66^{ab}	1219.91^{a}	0.0120	0.0934	325.667
k	0.042^{a}	0.036^{ab}	0.029^{b}	0.0018	0.40	0.035	0.032	0.0890	0.0075	0.019
m	0.474	0.438	0.337	0.5181	0.426	0.379	0.444	0.8630	0.8892	0.676
W_i	407.19^{b}	461.12^{a}	462.06^{a}	0.0233	407.42^{b}	436.29^{ab}	486.66^{a}	0.0024	0.0064	124.100
T_i	53.601^{b}	62.082^{ab}	72.245^{a}	0.0067	62.200	62.726	63.002	0.9902	0.0493	31.852
AGR_{14}	4.792^{b}	4.970^{ab}	5.513^{a}	0.0079	4.598^{b}	5.071^{ab}	5.606^{a}	0.0004	0.0002	0.539
AGR_{21}	5.365^{b}	5.456^{ab}	6.041^{a}	0.0485	5.172^{b}	5.586^{ab}	6.195^{a}	0.0029	0.0216	0.569
AGR_{28}	6.408^{b}	6.713^{ab}	7.336^{a}	0.0116	6.358^{b}	6.595^{b}	7.503^{a}	0.0013	0.0027	0.712
AGR_{35}	6.901^{b}	7.469^{ab}	7.865^{a}	0.0184	6.982^{b}	7.216^{b}	8.037^{a}	0.0066	0.0100	0.778
AGR_{42}	7.729^{b}	8.187^{ab}	8.818^{a}	0.0521	7.746^{b}	8.040^{ab}	8.948^{a}	0.0232	0.0595	1.042
AGR_{49}	8.289^{b}	8.830^{ab}	9.932^{a}	0.0141	8.243^{b}	9.011^{ab}	9.797^{a}	0.0236	0.0345	1.296
AGR_{56}	8.825^{b}	9.674^{ab}	10.208^{a}	0.0343	8.744^{b}	9.535^{ab}	10.428^{a}	0.0093	0.0254	1.234
AGR_{63}	8.997^{b}	9.838^{ab}	10.564^{a}	0.0430	8.950^{b}	9.773^{ab}	10.675^{a}	0.0241	0.0492	1.443
AGR_{70}	8.206^{b}	8.605^{ab}	10.219^{a}	0.0141	8.239^{b}	8.828^{ab}	9.963^{a}	0.0487	0.0339	1.649
AGR_{77}	6.488^{b}	8.218^{ab}	8.541^{a}	0.0368	6.527^{b}	8.093^{ab}	8.627^{a}	0.0392	0.0889	1.977
$AGR_{/84}$	5.957^{b}	7.441^{ab}	7.824^{a}	0.0411	5.818^{b}	7.333^{ab}	8.070^{a}	0.0155	0.0498	1.800
AGR_{91}	5.392^{b}	6.765^{ab}	7.222^{a}	0.0479	5.157^{b}	6.853^{ab}	7.369^{a}	0.0139	0.0495	1.787
AGR_{98}	4.594^{b}	6.041^{ab}	6.691^{a}	0.0185	4.746^{b}	6.057^{ab}	6.523^{a}	0.0474	0.0631	1.726

* W_0 (g), W_f (g), k (g per d), and m are initial weight, final body weight, coefficient of relative growth or maturing index, and the shape parameter, respectively. W_i; weight at the inflection point (g); T_i; Age at the inflection point (d); AGR: Absolute growth rate in different age (g/d); SEM: standard error of mean.

a-b: Different superscripts within a row shows significant different between energy and protein levels ($P<0.05$).

Table 5 Interaction effect of energy and protein on growth curve parameters and Absolute growth rate in different ages

ME (k cal/kg)	**2600**			**2800**			**3000**		
CP (%)	**17**	**19**	**21**	**17**	**19**	**21**	**17**	**19**	**21**
W_0	39.481	38.663	38.092	37.768	37.773	42.352	40.275	40.134	42.274
W_f	969.6	1101.7	1141.6	1040.4	1177.1	1252.4	1119.8	1194.2	1265.8
k	0.0490^{a}	0.0420^{ab}	0.0352^{ab}	0.0349^{ab}	0.0360^{ab}	0.0363^{ab}	0.0358^{ab}	0.0271^{b}	0.0248^{b}
m	0.5515	0.4670	0.4041	0.3621	0.3506	0.6012	0.3650	0.3200	0.3270
W_i	379.51^{b}	411.75^{ab}	430.30^{ab}	415.49^{ab}	438.94^{ab}	528.94^{a}	427.26^{ab}	458.18^{ab}	500.73^{ab}
T_i	50.47^{b}	54.55^{ab}	55.79^{ab}	53.67^{ab}	66.43^{ab}	66.15^{ab}	82.47^{a}	67.20^{ab}	67.07^{ab}
AGR_{14}	4.244^{b}	4.980^{b}	5.152^{b}	4.907^{b}	4.981^{b}	5.023^{b}	4.644^{b}	5.251^{b}	6.643^{a}
AGR_{21}	4.788^{b}	5.305^{ab}	6.001^{ab}	5.266^{ab}	5.434^{ab}	5.937^{ab}	5.461^{ab}	6.017^{ab}	6.646^{a}
AGR_{28}	5.832^{b}	5.906^{b}	7.487^{ab}	6.036^{b}	6.814^{ab}	7.288^{ab}	7.206^{ab}	7.066^{ab}	7.735^{a}
AGR_{35}	6.408^{b}	6.685^{b}	7.610^{ab}	7.519^{ab}	7.197^{ab}	7.691^{ab}	7.020^{ab}	7.766^{ab}	8.809^{a}
AGR_{42}	7.321^{b}	7.381^{b}	8.486^{ab}	7.918^{ab}	8.218^{ab}	8.425^{ab}	7.999^{ab}	8.521^{ab}	9.934^{a}
AGR_{49}	7.778^{b}	7.980^{ab}	9.110^{ab}	8.016^{ab}	9.230^{ab}	9.243^{ab}	8.934^{ab}	9.824^{ab}	11.038^{a}
AGR_{56}	7.911^{b}	9.002^{ab}	9.561^{ab}	8.702^{ab}	10.086^{ab}	10.233^{ab}	9.617^{ab}	9.517^{ab}	11.489^{a}
AGR_{63}	7.845^{b}	9.251^{ab}	9.896^{ab}	9.360^{ab}	10.070^{ab}	10.084^{ab}	9.646^{ab}	9.999^{ab}	12.047^{a}
AGR_{70}	7.047^{b}	8.314^{ab}	9.257^{ab}	8.658^{ab}	8.407^{ab}	8.751^{ab}	9.013^{ab}	9.762^{ab}	11.882^{a}
AGR_{77}	5.419	6.716	7.331	7.335	8.731	8.588	6.826	8.834	9.964
$AGR_{/84}$	4.547^{b}	6.166^{ab}	7.158^{ab}	6.732^{ab}	7.482^{ab}	8.109^{ab}	6.176^{ab}	8.351^{ab}	8.945^{a}
AGR_{91}	3.885^{b}	5.559^{ab}	6.734^{ab}	5.881^{ab}	6.737^{ab}	7.676^{ab}	5.706^{ab}	8.263^{a}	7.698^{ab}
AGR_{98}	3.679	4.525	5.577	4.971	6.090	7.062	5.587	7.557	6.930

* W_0 (g), W_f (g), k (g per d), and m are initial weight, final (mature weight) weight, coefficient of relative growth or maturing index, and the shape parameter, respectively. W_i; weight at the inflection point (g); T_i; Age at the inflection point (d); AGR: Absolute growth rate (g/d) in different age.

a-b: Different superscripts within a row shows significant different between treatments ($P<0.05$)