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Research article

Using non-linear models to describe growth curves for Thai black-bone chickens

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Abstract

Importance of the work: Modelling the growth curve of a chicken line is important for optimizing the management for both broiler and layer chickens. In the present study, a non-linear model was developed to estimate growth in a Thai black-bone chicken population.

Objectives: To determine an appropriate non-linear model to describe the growth curve in Thai black-bone chickens.

Materials & Methods: Individual body weights from 3,280 birds were collected at ages 0 wk, 2 wk, 4 wk, 6 wk, 8 wk, 10 wk and 12 wk. Three non-linear growth models (Gompertz, logistic, von Bertalanffy) were implemented using the Levenberg-Marquardt algorithm. The coefficient of determination (R^2), root mean squared error (RMSE) and mean absolute error (MAE) were used to determine the most appropriate model.

Results: Growth curves between male and female chickens were significantly ($p < 0.05$) different; the males grew faster than the females. The von Bertalanffy model provided the best fit for the growth curves in male and female chickens based on R^2, RMSE and MAE values. However, the R^2 values from the three non-linear growth models were all close to 1 ($R^2 > 0.9$). Hence, all models described very well the growth curves from day 0 to age 12 wk for black-bone male and female chickens.

Main findings: The results indicated that the three non-linear functions could be used to model growth in black-bone chickens. Further studies for the development of breeding programs are required that include genetic parameters in growth curve modeling and their relationships with other economically important traits.

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Introduction

Black-bone chicken (*Gallus gallus domesticus*) is one of the most popular and ubiquitous chickens in Thailand, because of its organoleptic and medicinal values (Khumpeerawat et al., 2021). Black-bone chicken products are desired in Asian countries because they are known as a functional food and they have desirable meat quality, with the skin color being a unique characteristic (Tian et al., 2007). Meat from black-bone chickens is black in color due to the large melanin content, a genetic condition called fibromelanosis (hyperpigmentation associated with the endothelin 3 gene) (Dorshorst et al., 2011). Melanin plays an important role in protecting against environmental stresses (Agustinho and Nosanchuk, 2017) and acts as a natural antioxidant in food produced using meat from black-bone chickens (Tu et al., 2009). Furthermore, black-bone chicken has special medicinal value; traditional Chinese medicine uses the meat from black-bone silky fowl as a health food (Tian et al., 2007).

Thai black-bone chicken (KU-Phuparn) was developed for both meat and egg production at Kasetsart University Chalermphrakiat Sakon Nakhon province campus, Thailand. The characteristics of the KU-Phuparn differ from the other black bone chicken in that the skin, bones, meat, beak, legs, and feet are black, but the feathers are white (Phongkaew and Khumpeerawat, 2017) (Fig. 1). Moreover, the single comb is a dark red color and is the most common comb characteristic for black-bone chicken. KU-Phuparn chickens are medium-sized (1.2–1.5 kg at maturity) and perform equally well in both cold and hot conditions. Females are solid layers producing 160–180 brown eggs per year and males make dependable meat birds. However, they mature faster than many other Thai native breeds but are slower maturing compared to commercial broiler breeds or lines.

Modelling the growth curve of black-bone chicken line is important for optimizing the management for both broiler and layer chickens. Development of growth curves may be a powerful tool to establish feeding programs and other management recommendations to improve feed conversion efficiency and increase productivity (Darmanikuhi et al., 2010; Nahashon et al., 2010; Kaplan and Gürcan, 2016). The growth traits include not only average daily gain, but the associated growth curve, which can be improved using genetic selection. Currently, Thai black-bone chicken producers select their breeding animals based on phenotypic performance traits such as harvest weight and visual appearance traits such as beak, leg and feet color, where black is the preferred color (Khumpeerawat et al., 2021). Hence, growth curve modeling is important and useful to improve growth performance traits in black-bone and other chicken breeds or lines. Several studies have utilized different non-linear functions to describe the growth curve including Gompertz (Laird, 1965), logistic (Nelder, 1961), and von Bertalanffy (von Bertalanffy, 1957). These mathematical models are widely used to describe the growth curve from food-producing animals and are commonly implemented using the non-linear least square method (Mouffok et al., 2019; Mata-Estrada et al., 2020). However, no reports were found in the scientific literature where a non-linear model was used to describe the growth curve in black-bone chickens under tropical conditions. Thus, the objective of this study was to evaluate three non-linear growth models (Gompertz, logistic and von Bertalanffy) to assess their ability to describe the growth curve of Thai black-bone chickens.

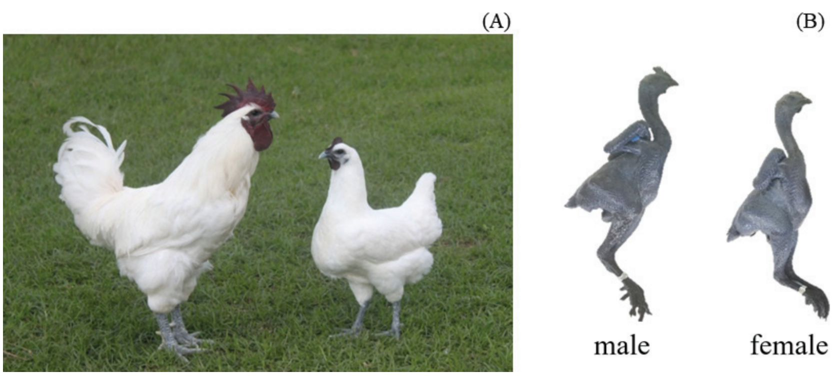

Fig. 1 (A) Live male (left) and female (right) Thai black-bone chickens; (B) harvested and defeathered male and female Thai black-bone chickens showing fibromelanosis phenotype

Materials and Methods

Ethics statements

This study was approved by the Institutional Animal Care and Use Committee (IACUC), Kasetsart University (Approval no. ACKU64-CSC-003) and by the Ethical Review Board of the Office of National Research Council of Thailand (NRCT license No. U1-04518-2559).

Animals, housing and management

The data from male and female KU-Phuparn (Thai black-bone) chickens were obtained from the Animal Research Farm on the Kasetsart University Chalermphrakiat Sakon Nakhon province campus. The chickens were reared in an open housing system. Twenty chickens were raised in each open pen. Each pen measured 1.4 m × 1.5 m × 2.5 m (width × depth × height), with floor litter (rice husks), one water bowl drinker and one feeder (plastic hopper, produced by Mitrkasetphand Co., Ltd., Thailand). Space allowance for each chicken was 0.1 m^2 that met or exceeded Good Agricultural Practices for broiler farm recommendations (The Agricultural Standards, 2009). The chickens were fed a commercial diet (pelleted) with 21% crude protein (CP), 3,200 kcal metabolizable energy (ME)/kg from age 0–4 wk and fed with 18% CP, 3,200 kcal ME/kg from age 5–12 wks. The diets fed during the experiment met or exceeded the nutritional requirements for chickens (National Research Council, 1994). Chickens were provided *ad libitum* access to feed and water throughout the experiment. The vaccination program was administered by the farm veterinarian and followed commonly utilized vaccination protocols implemented in the Thai commercial broiler industry. The management and feeding program were provided and followed the standard operation procedure from the Thai Agricultural Standard (TAS).

The individual records for each bird consisted of birth date, hatch, flock and generation. Individual bird body weight (BW) was recorded at age 0 wk, 2 wk, 4 wk, 6 wk, 8 wk, 10 wk and 12 wk using a digital scale (Tanita KD-200; Tanita Corp., Japan). Chicken records that contained incomplete BW information or missing data were deleted from the dataset. A bird with data considered an outlier was defined using the Mahalanobis distance method (Etherington, 2021, where a chi-square value for 7 degrees of freedom was used as the cut-off point to identify birds with corresponding outlying data. These chickens and their associated BW data that were classified as outliers were excluded from the final dataset. After editing, the dataset contained 3,280 birds (1,814 males and 1,466 females). Student's t test (alpha = 0.05 level of significance) was used to compare mean BW values between sexes.

Non-linear growth model

The Gompertz, logistic and von Bertalanffy non-linear models were fitted to the sets of bird BW measurements. Equations for the three non-linear models are provided in Table 1. Growth curve parameters for each model were estimated using the nlslm functions (Nonlinear least squares regression with the Levenberg-Marquardt algorithm; Moré, 1978) in the minpack.lm packages (Elzhov et al., 2016) in the R software package (R Core Team, 2020).

Table 1 Non-linear growth equations and coordinates for three non-linear growth models used to establish growth curves for the Thai black-bone chicken population

Model	Equation
Gompertz	$y = A \times \exp(-b \times \exp(-k \times t))$
Logistic	$y = A / (1 + b \times \exp(-k \times t)$
von Bertalanffy	$y = A \times (1 - b \times \exp(-k \times t)^3$

y = body weight at age t; A = asymptotic weight; b = integration constant; k = maturity rate; t = age in weeks

Cross validation method and model selection criteria

Repeated k-fold cross validation (where k is the number of folds) was used to evaluate the performance for the three non-linear models, as repeated k-fold cross-validation provides a way to reduce the error when estimating the mean model performance (Refaeilzadeh et al., 2016). The 10-fold cross validations were repeated five times for each model (most common practice reported in the scientific literature; Olson and Delen, 2008; Refaeilzadeh et al., 2016).

In each cross-validation fold: 1) the data were randomly divided into 10 subsets; 2) one of the 10 subsets was used as the test data (10%) and the remaining nine subsets were used as training data (90%); 3) the training data were used to train the model and the testing data were used to evaluate the model by estimating the prediction error. Steps 1 to 3 were repeated until the model had been trained and tested on all subsets. The cross-validation procedure was repeated five times. Finally, to calculate the overall prediction error, the average prediction errors across all folds and all repeats were calculated.

The coefficient of determination (R^2), root mean squared error (RMSE) and mean absolute error (MAE) of the prediction errors were used to assess non-linear model performance during the cross-validation procedure.

The R^2, RMSE and MAE were calculated using Equations 1–3:

$$R^2 = 1 - \frac{SSE}{SST} \quad (1)$$

where SSE is the residual sum of squares and SST is total sum of squares.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \quad (2)$$

where y_i is the observed BW at age i, $\hat{y}_i$ is the estimated BW at age i and n is the number of observations.

$$MAE = \frac{\sum_{i=1}^{n}|y_i - \hat{y}_i|}{n} \quad (3)$$

where y_i is the observed BW at age i, $\hat{y}_i$ is the estimated BW at age i and n is the number of observations.

The non-linear model with the lowest values for RMSE and MAE and the highest R^2 value was selected and utilized to identify the "best" model. Significance was tested at the $p < 0.05$ level.

Results and Discussion

The BW descriptive statistics for birds at different ages and from male and female chickens are presented in Table 2. The average ± SD BW at hatching (week 0) was 38.8 ± 7.6 g and 36.0 ± 7.3 g for male and female chickens, respectively, while the average BW at week 12 was 1,286.8 ± 165.9 g and 1,165.4 ± 139.4 g for male and female chickens, respectively. The average BW increased in a continuous manner as the age of both male and female chickens increased (Fig. 2). The growth curves for male and female chickens were significantly different, with the males growing faster than the females. In general, the black-bone male birds had greater asymptotic BW compared to the female birds. These results agreed with other reports, where the average hatching weight for males was greater than females and males grew faster than females (Aggrey, 2002; Mata-Estrada et al., 2020). The growth curves from other published studies varied depending on sex, genetic background and feeding program. Moharrery and Mirzaei (2014) compared commercial broilers and native chickens and indicated that the growth curve from native chickens differed from commercial broilers. Additionally, the chickens fed a diet containing 3,200 kcal ME/kg had a lower BW at the inflection point compared to the chickens fed a diet containing 2,658 kcal ME/kg.

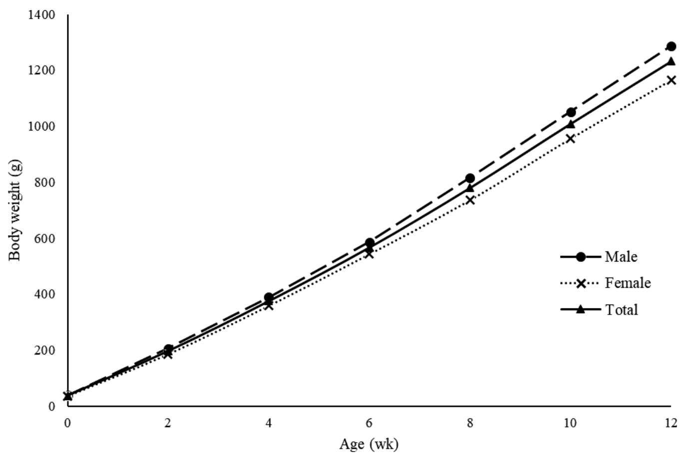

Fig. 2 Mean weekly body weight profile for male, female and total birds from the Thai black-bone chicken population

Table 2 Body weight (means ± SD) by age and sex of the Thai black-bone chicken population

Age (weeks)	Body weight (g)		
	Total (n = 3,280)	Male (n = 1,814)	Female (n = 1,466)
0 (at hatching)	37.6±7.6	38.8±7.6[a]	36.0±7.3[b]
2	196.8±36.1	205.6±32.5[a]	186.0±37.3[b]
4	375.2±67.0	388.5±66.5[a]	358.7±63.7[b]
6	566.8±94.2	585.7±96.3[a]	543.4±86.0[b]
8	780.0±129.3	815.3±134.5[a]	736.3±107.6[b]
10	1,009.2±152.9	1,052.0±156.9[a]	956.2±129.5[b]
12	1,232.5±165.9	1,286.8±165.9[a]	1,165.4±139.4[b]

n = number of observations;
Mean values within each row superscripted with different lowercase letters denote significant ($p < 0.05$) differences between males and females.

Growth curve modeling and parameter estimation

Growth curve parameter estimates for the Gompertz, logistic and von Bertalanffy models are shown in Table 3. The greatest estimated asymptotic BW (A) was observed using the von Bertalanffy model with values of 2,793.2 g for males and 2,433.0 g for females, whereas the lowest values were observed for the logistic model for both male and female chickens (1,548.0 g and 1,393.8 g, respectively). However, the predicted and observed values for BW at age 12 wk were not significantly different for males and females in all models (data not shown). Mata-Mata-Estrada et al. (2020) reported the logistic model had the lowest asymptotic BW value compared to the Gompertz, Richards and von Bertalanffy models for both male and female Mexican Creole chickens. Likewise, Aggrey (2002) and Mouffok et al. (2019) reported the lowest estimated asymptotic BW for the logistic model. In contrast, Moharrery and Mirzaei (2014) reported the lowest estimated asymptotic BW implementing the Richards model to evaluate data from a commercial strain and Iranian native chicken populations. Al-Samarai (2015) reported the weighted least squares function provided the lowest asymptotic BW. However, results from Al-Samarai (2015) indicated that the lowest asymptotic BW was achieved applying the logistic model compared to both the Gompertz and von Bertalanffy models.

In the present study, the greatest integration constant parameter (b) values were obtained implementing the logistic model (male = 13.3; female = 13.0) and the lowest values were achieved applying the von Bertalanffy model for both sexes (male = 0.7; female = 0.7). Likewise, the greatest maturity rate parameter (k) values were obtained implementing the logistic model (male = 0.342; female = 0.342) while the lowest values were obtained applying the von Bertalanffy model for both sexes (male = 0.095; female = 0.098). Predicted and observed BW growth curves from the three non-linear models utilized in the present study are presented in Fig. 3. The growth curves from all models show that BW increases to age 12 wk for both sexes. The predicted BW growth curve values obtained implementing the von Bertalanffy model were closer to the observed values than for growth curve values obtained applying either the Gompertz or logistic models. The predicted BW growth curve values from all models were greater than the observed values in the early and late weeks of the growth period (ages 0–1 wk and 8–10 wk, respectively) and lower than the observed values in weeks 3–5 for both sexes. Differences between the observed and predicted BW values were greater implementing the logistic model compared to the observed and predicted differences obtained applying the Gompertz and von Bertalanffy models. Thus, the predicted values had an S shape that followed the three growth functions, whereas the observed values from the present data had a flat S shape (Fig. 3). These curve shape differences may have been influenced by the fixed inflection point associated with the three functions, because each has different characteristics. The logistic function describes a symmetric growth curve that has an inflection point weight at half of the asymptotic BW, while the Gompertz function describes an asymmetrical growth curve that has an inflection point BW at approximately 37% of the asymptotic weight; on the other hand, the von Bertalanffy function has a flexible inflection point at about 30% of the asymptotic BW (Thornley and France, 2007; Teleken et al., 2017).

Table 3 Growth curve parameter estimates ± SE for three non-linear growth models in the Thai black-bone chicken population

Group	Model	Growth curve parameter		
		A	b	k
Total	Gompertz	1986.5±18.6	3.26±0.01	0.159±0.002
	Logistic	1479.1±7.0	13.16±0.10	0.342±0.002
	Von Bertalanffy	2631.4±39.6	0.71±0.01	0.096±0.001
Male	Gompertz	2091.1±26.0	3.27±0.01	0.158±0.002
	Logistic	1548.0±9.6	13.33±0.14	0.342±0.003
	Von Bertalanffy	2793.2±56.4	0.71±0.01	0.095±0.002
Female	Gompertz	1855.2±23.2	3.24±0.01	0.160±0.002
	Logistic	1393.8±8.9	12.95±0.14	0.342±0.003
	Von Bertalanffy	2433.0±48.2	0.71±0.01	0.098±0.002

A = asymptotic weight; b = integration constant; k = maturity rate

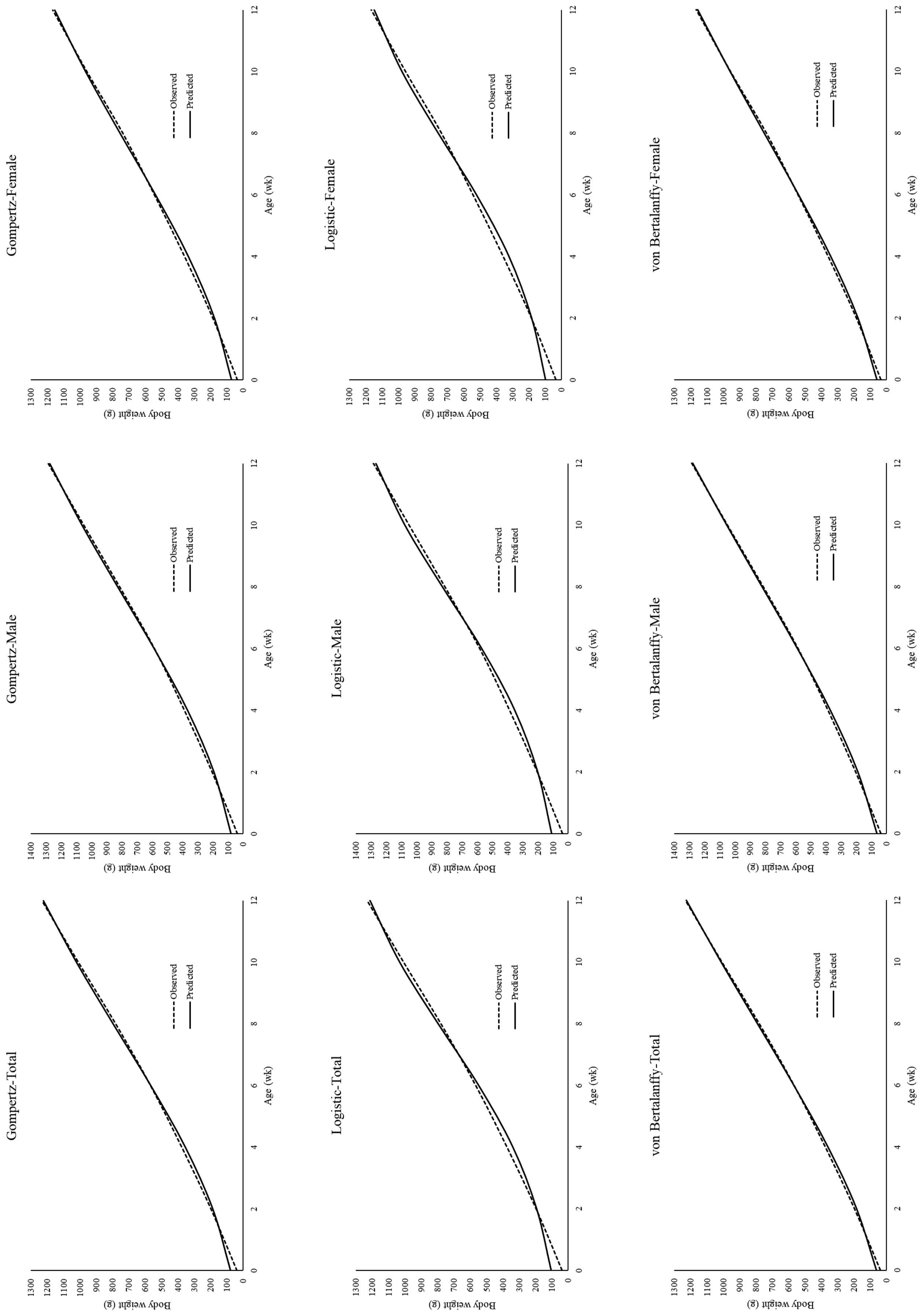

Fig. 3 Growth curves for male and female chickens and combined (total) predicted using Gompertz, logistic, and von Bertalanffy growth models based on observed data from the Thai black-bone chicken population

Comparison of models

The goodness-of-fit results associated with the three non-linear models from repeated k-fold cross validation are presented in Table 4. The von Bertalanffy model had the lowest RMSE and MAE values for both males (RMSE = 110.9; MAE = 77.6) and females (RMSE = 94.0; MAE = 67.0) and the greatest R^2 values both males (0.94) and females (0.94) compared to the other models used in the present study. The logistic model was the poorest model based on the RMSE and MAE values for both males (RMSE = 114.9; MAE = 84.6) and females (RMSE = 98.2; MAE = 74.4). The von Bertalanffy growth model was the best-fitting model from three studies in the scientific literature (Yang et al., 2006; Adenaike et al., 2017; Mata-Estrada et al., 2020). Furthermore, the von Bertalanffy model was the best model for estimating BW from age 4 wk onward in lightweight broilers (harvest weight ≤ 2,500g) according to Mouffok et al. (2019). On the other hand, Rizzi et al. (2013), Moharrery and Mirzaei (2014) and Osei-Amponsah et al. (2014) reported that the Richards model produced the best fit for data from commercial broilers and native chickens, while Zhao et al. (2015) and Mouffok et al. (2019) reported that the Gompertz model produced the best fit for data from commercial broilers and Chinese native chickens, respectively. Furthermore, Al-Samarai (2015) observed that weighted least squares produced the best fit for data from commercial broilers, while Manjula et al. (2018) reported the logistic model had the best convergence properties. The present study did not investigate the Richards model because the parameter m (shape parameter in the Richards model) has no direct biological meaning, even though it impacts the age to mature weight and the inflection point (Teleken et al., 2017). The weighted least squares model is not a non-linear function that is commonly used to describe the growth curve in chickens. Hence, the present study focused on the three non-linear models.

Although determining the best model varies depending on the population structure and other factors such as genetic background (Moharrery and Mirzaei, 2014), slaughter weight (Mouffok et al., 2019) and feeding program (Moharrery and Mirzaei, 2014), the R^2 values from the Gompertz, logistic and von Bertalanffy models were close to 1 (> 0.9) for both sexes, indicating that all models described the growth curve from Thai black-bone chickens in a similar and accurate manner. Other published coefficient of determination values from the Gompertz, logistic, and Richards models were also high ($R^2 > 0.9$), demonstrating that a bird's BW can essentially be explained by its age (Aggrey, 2002; Moharrery and Mirzaei, 2014; Al-Samarai, 2015; Zhao et al., 2015; Manjula et al., 2018; Mouffok et al., 2019). Additionally, the von Bertalanffy model provided a flexible inflection point for the asymptotic BW compared to the Gompertz and logistic models (Thornley and France, 2007; Teleken et al., 2017). Because the von Bertalanffy model provides a flexible function, it could be used as a generalized model to describe the BW growth curve in the present study.

In conclusion, the BW growth curves for Thai black-bone male and female chickens were significantly different, with the males growing faster than the females. Based on the R^2, RMSE and MAE values, the von Bertalanffy growth curve was determined to be the most appropriate model to describe the BW growth curve for both sexes. These results indicated that a non-linear model could be utilized to evaluate growth in a Thai black-bone chicken population. However, all the models evaluated in the present study performed well ($R^2 > 0.9$) and adequately predicted BW growth curve parameters.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

Support facilities were provided by Kasetsart University Chalermphrakiat Sakon Nakhon province campus. The Animal Research Farm staff, Kasetsart University Chalermphrakiat Sakon Nakhon province campus collected and provided the data.

Table 4 Goodness-of-fit statistics ± SE from cross-validation used to evaluate three non-linear growth models in the Thai black-bone chicken population

Group	Model	R^2	RMSE	MAE
Total	Gompertz	0.93±0.01	110.1±4.7	77.3±2.4
	Logistic	0.93±0.01	113.1±3.9	82.1±2.4
	Von Bertalanffy	0.93±0.00	109.2±4.1	75.0±2.3
Male	Gompertz	0.93±0.01	111.8±5.1	79.8±2.7
	Logistic	0.93±0.01	114.9±4.5	84.6±2.6
	Von Bertalanffy	0.94±0.01	110.9±5.1	77.6±3.0
Female	Gompertz	0.94±0.01	95.0±4.3	69.3±3.1
	Logistic	0.94±0.01	98.2±5.2	74.4±3.5
	Von Bertalanffy	0.94±0.01	94.0±4.6	67.0±3.0

R^2 = coefficient of determination; RMSE = root mean squared error; MAE = mean absolute error

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