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COMPARISON OF PARAMETER ESTIMATES OF NON-LINEAR GROWTH MODEL IN DIFFERENT CHICKEN BREEDS USING BAYESIAN APPROACH WITH NORMAL DISTRIBUTION DATA

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ABSTRACT

Bayesian statistics is a system for describing epistemological uncertainty using the mathematical language of probability while growth models provide valuable information for livestock improvement programs and decision-making. In this study, the ability of four non-linear growth models (Gompertz, logistic, Richards and von Bertalanffy) were evaluated to predict the growth of three indigenous breeds (Normal Feathered, Frizzle Feathered and Naked Neck chickens), one locally developed crossbred chicken (FUNAAB Alpha) and three exotic breeds (Nera Black, White Leghorn and Giriraja). Data for body weight were collected every week from 993 birds for 20 weeks. The non-linear growth models were used to fit the body weight data using Bayesian approach under normal distribution data. The parameters in the models; asymptotic weight, integration constant, maturing rate, age at inflection point and weight at inflection point for the logistic, Gompertz, Richards and von Bertalanffy growth models were estimated for each breed using WinBUGS (version 1.4.3) to read the model, priors and posterior data, and run the Markov Chain Monte Carlo simulation (MCMC). The models were adjusted for best fit using Bayesian Information Criterion (BIC). The results showed that von Bertalanffy model had the lowest maturing rate (0.07, 0.08, 0.08, 0.06, 0.05, 0.07 and 0.08) and predicted the highest asymptotic weight (2104.50 g, 1963.00 g, 1821.75 g, 2668.50 g, 3167.00 g, 2269.50 g and 3326.00 g) among the models for Naked Neck, Frizzle Feather, Normal Feather, FUNAAB Alpha, Nera Black, White Leghorn and Giriraja chickens, respectively. The parameter estimates in Gompertz and Richards models were relatively consistent within the breed compared to other models with a variation difference of between 1.5 and 2.0 % while the range between 8.3 and 10.0 % was recorded within FUNAAB Alpha and Nera Black. According to the values obtained in Bayesian information criterion, the von Bertalanffy model had the lowest value for all the breeds. In conclusion, Bayesian model should be considered in growth-related decision-making and selection program involving the breeds examined in this study.

Key words: Von Bertalanffy; exotic chicken; Gompertz; non-linear model; probability; logistic; Richards

INTRODUCTION

In the animal industry, a major prime trait of interest is body weight as it reflects growth and developmental expression of the animal. It is non-linear trait and it is affected by genetic and environmental effects (Ibáñez-Escriche and Blasco 2011). Genetic improvement in poultry worldwide is heavily focused on selection for higher final body weight at a given age, especially for meat breeds. Although commercial broilers are mostly sold by their final body weight, it is important to carefully consider how this weight is attained (Hagan, 2022). Growth, a complex physiological kinetics, is a multidirectional phenomenon that cannot be easily understood linearly because it is longitudinal in nature. Growth models have been reported to have

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the potential to represent the entire growth phase of chickens and the parameters in the models have biological meanings (Kizilkaya *et al*., 2006).

Growth models are non-linear in nature, capable of fitting animal growth which is generally non-linear in shape (S-shaped), characterized by exponential and declining phase. These non-linear models have the ability to represent the weight gain, describe animal's growth regularity (Franco *et al.*, 2011) and contain parameters that can evaluate some important biological traits like weight at maturity, maturing rate and age at peak weight. These parameters are useful tools to provide estimates of the daily feed requirements, to evaluate the influence of the environmental conditions on the weight gain of the animal, to predict the optimum slaughter age (Teleken *et al*., 2017) or to estimate the relationship between feed requirements and body weight which plays a crucial role in animal husbandry (Sengul and Kiraz, 2005). The parameters of these non-linear models can reduce a series of age-weight data to a few parameters with biological relevance in growth equation and also help to eliminate the effect of error effectively (Aggrey, 2002; Teleken *et al*., 2017). Non-linear models have been applied on a wide range of animals, including birds (Nahashon *et al*., 2006), mammals (Franco *et al*., 2011), fishes (Santos *et al*., 2013) and amphibians (Mansano *et al*., 2013). Based on research and available literature, the mostly used non-linear models for animal growth prediction are logistic, Gompertz, Brody, von Bertalanffy and Richards growth models (France *et al*., 1996). Furthermore, logistic, Gompertz and von Bertalanffy models are often used to fit the growth curve of poultry (Eleroglu *et al*., 2014). Tholon and Queroiz (2007) used Gompertz, brody, von Bertalanffy and logistic models for the analysis of growth curves in tinamous, Zhao *et al*., (2015) used logistic, Gompertz and von Bertalanffy to study the growth and development of Shaobo, Huaixiang and Youxi chickens.

Bayesian statistics is a system for describing epistemological uncertainty using the mathematical language of probability (Spiegelhalter and Rice, 2009). Bayesian methods reduce statistical inference to problems of probability theory, thereby minimizing the need for a completely new concept (Bernardo and Rueda, 2002). Over the last two decades, there has been a revolution in which Bayesian methods have become a highly popular and effective tool for the applied statisticians (Lenhard, J., 2022). It takes into account both the prior knowledge about the parameter and the observed data. The final step is concerned with the evaluation of the fit of the model to the data and the implication of the resulting posterior distribution and sensitivity of the conclusions to the assumptions (Gelman *et al*., 2003). This study aimed at comparing the parameter estimates between four non-linear growth models, and the model that can best fit the data.

MATERIALS AND METHODS

The growth data of 993 offspring of seven genotypes of chicken, namely Bovan Nera (NB) – 133, White Leghorn (WL) – 93, Giriraja (GR) – 105, Naked Neck (NN) – 197, Frizzle Feather (FF) – 164 and Normal Feather (NF) – 186, and FUNAAB Alpha Breed (BA) – 115, were taken weekly for 20 weeks. The growth measurements were performed using sensitive scale with sensitivity of 0.05 g and the capacity of two decimal digits.

Bayesian approach on normal error model

The growth model for a single experimental unit data obtained from animal i was expressed as:

$BW_{ij} = f(\vartheta_i, t_{ij}) + e_{ij}$ ..... $i = 1,..., N$ and $j = 1,...., n_i$ (Kizilkaya *et al*., 2006)

BW in the model is assumed to be normally distributed with mean μ_{ij} and variance $\frac{1}{\tau_e}$ for normal distribution of data with error e_{ij}.

Here, f is the non-linear function relating the response variable, body weight (BW_{ij}), to time (t_{ij}) during which the j^{th} observation was taken, ϑ_i is a vector of unknown parameters, N is the number of animals and n_i is the number of measurements taken from animal i, e is the residuals error with the assumption of $e_i \sim N(\theta,\sigma^2 I_i)$ where $\sigma^2 I_i$ is the residual variance structure for all subjects, assuming that no covariance structure exists between the residuals of the model. Thus, $f(\vartheta_i, t_{ij})$ is one of the different types of growth curves used for the analysis of the data set. Frequently used non-linear functions, namely logistic, Gompertz, Richards and von Bertalanffy were used to fit the growth data of indigenous chickens, improved chicken and locally adapted exotic chickens. These functions have been used in describing growth pattern in animal production. The mathematical notations for the different growth models are presented in Table 1. A typical growth curve

Table 1. Equations for cases of logistic, Gompertz, Richards and Von Bertalanffy model

Model	$BW_{ij} = f(\theta_i, t_{ij}) + e_{ij}$	t_{inf}	W_{inf}
Logistic	$BW_{ij} = A_i(1 + B_i \exp\{-K_i t_{ij}\})^{-1} + e_{ij}$	$-\frac{\log\left(\frac{1}{B_i}\right)}{K_i}$	$\frac{A_i}{2}$
Gompertz	$BW_{ij} = A_i \exp\{-B_i \exp\{-K_i t_{ij}\}\} + e_{ij}$	$-\frac{\log(B_i)}{K_i}$	$\frac{A_i}{2.7182}$
Richards	$BW_{ij} = A_i(1 + B_i \exp\{-K_i t_{ij}\})^{\left(-\frac{1}{m_i}\right)} + e_{ij}$	$-\frac{\ln\left(\frac{m_i}{B_i}\right)}{K_i}$	$A_i(m_i + 1)^{\left(-\frac{1}{m_i}\right)}$
Von Bertalanffy	$BW_{ij} = A_i(1 - B_i \exp\{-K_i t_{ij}\})^3 + e_{ij}$	$\frac{\log(B_i) + \log(3)}{K_i}$	$\frac{8A_i}{27}$

of poultry generally composes of the following features: an exponential phase of growth from hatching (t = 0), a point of inflection at which the growth rate is peak and weight is maximum, a decaying phase during which growth rate increases at a decreasing rate and a limiting value called asymptotic (mature) weight.

The BW_{ij} stands for the body weight of the bird at age (week) t_{ij}; A stands for the asymptotic weight or mature weight as age approaches infinity ($t_i = \infty$); B stands for integration constant defining the degree of maturity at $t_i = 0$; k stands for maturing index as an expression of the growth rate relative to mature weight; m in Richards growth model is the shape parameter determining the position of the inflection point at which the auto acceleration growth phase passes into the auto retardation phase; t stands for the age of the bird at any particular time (Kizilkaya, *et al*, 2006). t_{inf} stands for the time at which the inflection was reached; and W_{inf} weight of the animal at the point of inflection. The distribution of the model parameters (*A*, *B* and *k*) is assumed to be normal. The prior and posterior distributions were extrapolated using the method described by Firat *et al*. (2016). The error variance was assigned a scaled inverted chi-square distribution with hyper-parameters υ and s^2. Where υ is the degree of belief and s^2 is the scaling factor of the inverted chi-square distribution.

The growth curve parameters (A, B and *k*) for the logistic, Gompertz, Richards and von Bertalanffy growth models were estimated for each chicken using WinBUGS (version 1.4.3) to read the model, prior and posterior, and run the Markov Chain Monte Carlo simulation (MCMC)

Prior distribution

$$h(\theta_1|\bar{\theta}_1) \propto \frac{1}{\bar{\sigma}_A\bar{\sigma}_B\bar{\sigma}_k} exp\left[-\frac{1}{2}\left(\frac{(A-\mu_A)^2}{\bar{\sigma}_A^2} + \frac{(B-\mu_B)^2}{\bar{\sigma}_B^2} + \frac{(k-\mu_k)^2}{\bar{\sigma}_k^2}\right)\right]$$

Posterior distribution

$$\pi(\theta_{1,}\, \sigma^2|y,t) \propto (\sigma^2)^{\frac{1}{2}(\mu+\upsilon+2)} \text{ X } exp\left[-\frac{1}{2}\left(+\frac{\sum_{j=1}^{n}(y_j - f_1[t_j,\ \theta_2])^2 + \nu s^2}{\sigma^2} + \frac{(B-\mu_B)^2}{\bar{\sigma}_B^2} + \frac{(k-\mu_k)^2}{\bar{\sigma}_k^2}\right)\right]$$

(Spiegelhalter *et al.*, 2003). The prior distributions for parameters (hyperparameters) in the model above are listed thus:

$$\mu_A \sim Normal(0,10000)$$
$$\mu_B \sim Normal(0,10000)$$
$$\mu_K \sim Normal(0,10000)$$
$$\mu_m \sim Normal(0,10000)$$
$$\tau_A \sim Gamma(0.001,0.001)$$
$$\tau_B \sim Gamma(0.001,0.001)$$
$$\tau_K \sim Gamma(0.001,0.001)$$
$$\tau_m \sim Gamma(0.001,0.001)$$
$$\tau_\varepsilon \sim Gamma(0.001,0.001)$$

t_{inf} and W_{inf} for each chicken were calculated by using estimated growth curve parameters. Then, the arithmetic mean, standard error of arithmetic mean, minimum and maximum values of the estimates of growth curve parameters and the age and weight at the inflection point (t_{inf} and W_{inf}) were calculated by using R project (Hornik, 2013) for the breeds within Logistic, Gompertz, and Von Bertalanffy growth models.

Model comparison

Model comparisons among logistic, Gompertz, Richards and von Bertalanffy growth models in this study were carried out using the Deviance Information Criteria (DIC), which was introduced by Spiegelhalter *et al.* (2002),

$$DIC(m) = 2\overline{D(\boldsymbol{\theta}_m, m)} - D(\bar{\boldsymbol{\theta}}_m, m) = D(\bar{\boldsymbol{\theta}}_m, m) + 2p_m$$

where $D(\boldsymbol{\theta}_m, m)$ is the usual deviance measure, which is equal to minus twice the log-likelihood

$$D(\boldsymbol{\theta}_m, m) = -2\log f(\boldsymbol{y} \mid \boldsymbol{\theta}_m, m)$$

and $\overline{D(\boldsymbol{\theta}_m, m)}$ is its posterior mean, which can be interpreted as the number of "effective" parameters for model m given by $p_m = \overline{D(\boldsymbol{\theta}_m, m)} - D(\bar{\boldsymbol{\theta}}_m, m)$ and $DIC(m) = 2\overline{D(\boldsymbol{\theta}_m, m)} - D(\bar{\boldsymbol{\theta}}_m, m)$ is the posterior mean of the parameters involved in model m, where m is logistic, Gompertz, Richards, or von Bertalanffy growth model.

DIC is particularly useful in Bayesian model selection problems where the posterior distributions of the models have been obtained by MCMC simulation. DIC is a Bayesian measure of the goodness of model fit with a penalty of model complexity. In general, models with smaller DIC should be preferred over models with larger DIC.

RESULTS

The asymptotic weight (*A*) among the four growth models based on Bayesian approach is presented in Table 2. The table showed that von Bertalanffy predicted the highest asymptotic weight (NN = 2104.5 g, FF = 1963.00 g, NF = 1821.75 g, BA = 2668.50 g, NB = 3167.00 g, WL = 2269.50 g and GR = 3326.00 g) in all the breeds followed by Logistic. It could further be observed from the table that the variations between

Table 2. Asymptotic weight in grams using the four growth models

Breed	Logistic	Gompertz	Richards	Von Bertalanffy
Indigenous				
NN	1227.00 ± 26.95	1612.25 ± 68.28	1579.25 ± 63.90	2104.50 ± 142.38
FF	1200.00 ± 27.98	1541.25 ± 67.50	1503.00 ± 62.40	1963.00 ± 128.75
NF	1124.00 ± 27.20	1435.25 ± 66.10	1417.25 ± 64.50	1821.75 ± 139.35
Crossbred				
BA	1353.00 ± 44.23	1896.50 ± 115.50	1839.50 ± 111.3	2668.50 ± 265.13
Exotic				
NB	1495.50 ± 47.73	2167.50 ± 127.58	2110.25 ± 126.08	3167.00 ± 304.60
WL	1232.90 ± 37.98	1666.00 ± 97.95	1640.25 ± 94.43	2269.50 ± 213.80
GR	2025.78 ± 41.50	2600.75 ± 94.75	2561.75 ± 92.68	3326.00 ± 192.40

NN = Naked Neck, FF = Frizzle Feathered, NF = Normal Feathered, BA = FUNAAB Alpha, NB = Nera Black, WL = White Leghorn, GR = Giriraja

Gompertz and Richards are relatively small when compared to logistic, even though Gompertz had the higher estimated values than Richards. The exotic breeds had the higher asymptotic weight than the indigenous breeds. However, among the indigenous breeds, the highest asymptotic weight was estimated for Naked Neck chickens.

Table 3 presents the estimated integration constant by the four models for all the breeds. The integration constant as estimated by Bayesian statistics was highest in logistic, followed by Gompertz, von Bertalanffy and Richards. The estimates revealed a wide variation between the values obtained in logistic and other models with the least values recorded in von Bertalanffy. Between the breeds, Frizzle Feathered chickens (Logistic = 19.04 g, Gompertz = 3.87 g, Richards = 0.14 g and Von Bertalanffy = 0.79 g) had the highest estimated value.

As shown in Table 4, the maturing rate for all the breeds estimated by the models revealed that logistic model recorded the highest estimated value in all the breeds (between 0.0022 and 0.25). The maturing rate estimates for Gompertz and Richards are relatively similar. However, the highest values recorded in logistic doubled the values recorded in both Gompertz and Richards while the lowest values recorded in von Bertalanffy was one third of the values recorded in logistic.

Table 3. Integration constant using the four growth models

Breed	Logistic	Gompertz	Richards	Von Bertalanffy
Indigenous				
NN	18.91 ± 0.83	3.85 ± 0.77 ± 10^{-1}	0.14 ± 0.29 ± 10^{-1}	0.79 ± 0.97 ± 10^{-2}
FF	19.04 ± 0.99	3.87 ± 0.93 ± 10^{-1}	0.14 ± 0.26 ± 10^{-1}	0.79 ± 1.17 ± 10^{-2}
NF	16.27 ± 0.83	3.61 ± 0.82 ± 10^{-1}	0.13 ± 0.26 ± 10^{-1}	0.76 ± 1.08 ± 10^{-2}
Crossbred				
BA	18.59 ± 0.91	3.81 ± 0.77 ± 10^{-1}	0.14 ± 0.32 ± 10^{-1}	0.78 ± 0.90 ± 10^{-2}
Exotic				
NB	18.77 ± 0.81	3.83 ± 0.67 ± 10^{-1}	0.14 ± 0.31 ± 10^{-1}	0.78 ± 0.75 ± 10^{-2}
WL	17.47 ± 0.97	3.72 ± 0.91 ± 10^{-1}	0.13 ± 0.28 ± 10^{-1}	0.77 ± 1.13 ± 10^{-2}
GR	18.18 ± 0.82	3.80 ± 0.80 ± 10^{-1}	0.13 ± 0.29 ± 10^{-1}	0.78 ± 1.01 ± 10^{-2}

NN = Naked Neck, FF = Frizzle Feathered, NF = Normal Feathered, BA = FUNAAB Alpha, NB = Nera Black, WL = White Leghorn, GR = Giriraja

Table 4. Maturing rate using the four growth models

Breed	Logistic	Gompertz	Richards	Von Bertalanffy
Indigenous				
NN	0.24 ± 0.66 ± 10^{-2}	0.11 ± 0.50 ± 10^{-2}	0.12 ± 0.52 ± 10^{-2}	0.07 ± 0.44 ± 10^{-2}
FF	0.25 ± 0.76 ± 10^{-2}	0.12 ± 0.57 ± 10^{-2}	0.13 ± 0.61 ± 10^{-2}	0.08 ± 0.48 ± 10^{-2}
NF	0.24 ± 0.76 ± 10^{-2}	0.12 ± 0.59 ± 10^{-2}	0.12 ± 0.59 ± 10^{-2}	0.08 ± 0.52 ± 10^{-2}
Crossbred				
BA	0.22 ± 0.76 ± 10^{-2}	0.10 ± 0.54 ± 10^{-2}	0.11 ± 0.60 ± 10^{-2}	0.06 ± 0.48 ± 10^{-2}
Exotic				
NB	0.22 ± 0.69 ± 10^{-2}	0.10 ± 0.49 ± 10^{-2}	0.10 ± 0.53 ± 10^{-2}	0.05 ± 0.42 ± 10^{-2}
WL	0.23 ± 0.87 ± 10^{-2}	0.11 ± 0.66 ± 10^{-2}	0.11 ± 0.69 ± 10^{-2}	0.07 ± 0.59 ± 10^{-2}
GR	0.25 ± 0.88 ± 10^{-2}	0.12 ± 0.48 ± 10^{-2}	0.12 ± 0.53 ± 10^{-2}	0.08 ± 0.43 ± 10^{-2}

NN = Naked Neck, FF = Frizzle Feathered, NF = Normal Feathered, BA = FUNAAB Alpha, NB = Nera Black, WL = White Leghorn, GR = Giriraja

Table 5. Age at inflection point using four growth models

Breed	Logistic	Gompertz	Richards	Von Bertalanffy
Indigenous				
NN	12.15 ± 0.25	11.83 ± 0.43	11.78 ± 0.40	12.35 ± 0.73
FF	11.78 ± 0.28	11.28 ± 0.43	11.20 ± 0.40	11.53 ± 0.65
NF	11.55 ± 0.30	11.00 ± 0.48	11.02 ± 0.48	11.18 ± 0.78
Crossbred				
BA	13.03 ± 0.38	14.28 ± 0.65	13.15 ± 0.63	14.63 ± 1.15
Exotic				
NB	13.58 ± 0.35	12.18 ± 0.60	14.13 ± 0.68	16.15 ± 1.20
WL	12.30 ± 0.35	12.18 ± 0.60	12.20 ± 0.60	13.08 ± 1.05
GR	11.88 ± 0.23	11.43 ± 0.38	11.40 ± 0.35	11.73 ± 0.60

NN = Naked Neck, FF = Frizzle Feathered, NF = Normal Feathered, BA = FUNAAB Alpha, NB = Nera Black, WL = White Leghorn, GR = Giriraja

Table 6. Weight at inflection point using four growth models

Breed	Logistic	Gompertz	Richards	Von Bertalanffy
Indigenous				
NN	613.55 ± 13.48	593.13 ± 24.13	590.70 ± 23.93	623.48 ± 42.20
FF	600.08 ± 14.00	566.98 ± 24.85	561.98 ± 23.40	581.63 ± 38.15
NF	562.03 ± 13.60	527.93 ± 24.30	530.48 ± 24.20	539.78 ± 41.28
Crossbred				
BA	676.53 ± 22.10	697.75 ± 42.50	687.88 ± 41.58	790.65 ± 78.55
Exotic				
NB	747.68 ± 23.85	797.33 ± 46.93	789.30 ± 47.18	938.28 ± 90.23
WL	616.40 ± 19.00	612.93 ± 36.05	613.60 ± 35.35	672.43 ± 63.35
GR	1012.80 ± 20.78	956.83 ± 34.85	957.55 ± 34.78	985.63 ± 57.00

NN = Naked Neck, FF = Frizzle Feathered, NF = Normal Feathered, BA = FUNAAB Alpha, NB = Nera Black, WL = White Leghorn, GR = Giriraja

Table 5 presents the estimated age at inflection point (t_{inf}) for all the breeds using all four growth models. Pattern of variation for the predicted age at the inflection parameter was not consistent across the models. Estimated values obtained in Gompertz and Richards are closely related, resulting in some of the lowest values. Logistic model predicted the highest values in Frizzle Feathered chickens (11.78 weeks), Normal Feathered (11.55 weeks) and Giriraja chickens (11.88 weeks) while Naked Neck chickens (12.35 weeks), FUNAAB Alpha chickens (14.63 weeks), Nera Black chickens (16.15 ± 1.20) and White Leghorn chickens (13.08 ± 1.05) had the highest estimates in Von Bertalanffy model. The difference between the lowest age at inflection point in Gompertz for Normal Feathered (11.00 weeks) and the highest in von Bertalanffy for Nera Black (16.15 weeks) was up to about 5 weeks.

As observed in Table 6, the estimated weight at inflection in the four growth models showed that the predictions of Gompertz and Richards are closely related for all the breeds, compared to von Bertalanffy and logistic. Von Bertalanffy predicted the highest values for the crossbred (790.65 g), NB (938.28 g) and WL (672.43 g), while logistic was highest in GR (1012.80 g).

Table 7 showed the values for the best fit in the four growth models based on Deviance Information Criteria (DIC). It was observed that Von Bertalanffy produced the lowest DIC value for all the breeds, although with lean variations compared to Gompertz. Richards and logistic have fairly higher Deviance Information Criteria compared to the other two models.

Table 7. Deviance information criteria for the best fit

Breed	Logistic	Gompertz	Richards	Von Bertalanffy
Indigenous				
NN	236195	236001	236258	235799
FF	238766	238510	238800	238329
NF	236043	235878	235899	235774
Crossbred				
BA	240766	240581	240811	240547
Exotic				
NB	239731	239386	239816	239306
WL	242417	242158	242482	242110
GR	240431	240166	240325	240050

NN = Naked Neck, FF = Frizzle Feathered, NF = Normal Feathered, BA = FUNAAB Alpha, NB = Nera Black, WL = White Leghorn, GR = Giriraja

DISCUSSION

The parameter estimates for non-linear models are biological traits with important information vital to livestock production decision-making. The asymptotic weight in an animal growth curve, is the maximum weight that an animal can reach as it grows, mostly affected by genotype and environment interactions (Narinç *et al*. 2010), and this is an important trait for breeders and producers. The different growth models used in this study showed variations in estimated asymptotic weight with von Bertalanffy growth model producing the highest asymptotic weight for all the breeds. This could be due to the fact that von Bertalanffy model is less sensitive to data errors and outliers compared to other models. This could also be due to the highest maturing rate recording in the model over other models which delays time to asymptotic and inflection point (Narinc *et al*., 2010). The rate at which the inflection point is attained is called the maturing rate while the weight attained at inflection point is directly proportional to the asymptotic weight (Pesti *et al*., 2019). The study also showed that the variation between estimates of asymptotic weight varies between the models (Raji *et al*., 2014). In their study, Gurcan *et al*. (2010) reported higher asymptotic weight in Gompertz followed by Richards and logistic. However, the overall growth of an animal is determined by the difference between the asymptotic weight and the integration constant (Gous *et al*., 2018). The integration constant on the other hand, is the vertical position (weight) of the growth curve at time t = 0. It is the initial weight of the animal. The asymptotic weight is considered the peak of the curve, although the weight does not drop at this point. Rather, the point of inflection begins when the growth curves changes from concave to convex and the growth starts to decline. The indication of biological relevance of Von Bertalanffy model, which is based on physiological principle of living organism, is more applicable in this study on poultry. Naked Neck produced the highest asymptotic estimate among the indigenous breeds which could be an indication of superiority of the Naked Neck gene. Furthermore, the study revealed that despite having the highest integration constant in logistic model, it estimated the lowest asymptotic weight. This could be due to the faster maturing rate achieved to reach inflection point earlier than other models which showed that the model can be used to fit empirical data with the assurance of more realistic growth curves, better accurate predictions of future growth and increased flexibility (Triambak *et al*., 2021; Abe *et al*., 2022). The highest integration constant estimate obtained in Frizzle Feather and Naked Neck may be reflective of their respective frizzle and Naked Neck genes, associated with inherent adaptability, which allows for earlier growth while other breeds are still acclimating. Additionally, Logistic model predicted that the birds attained asymptotic weight faster than other models because higher maturing rate indicates faster growth and earlier maturity.

The pattern of variation for the predicted age at inflection parameter (tinf) obtained in Gompertz and Richards are similar, predicting some of the lowest values. This showed that in the event of considering either of the model, none was significantly better than the other. Logistic on the other hand predicted the highest values in the indigenous, while von Bertalanffy did for the exotic breeds. The lowest age at inflection point estimated in Normal Feathered could be assumed that the birds does not possess as much adaptive capability as with other indigenous breed in relation to feather arrangement (Chen and Wen-Hsiung, 2018; Abe *et al*., 2022). The estimated age at inflection point for all the growth models was moderate (between 11.00 and 12.35 weeks) except in few cases where it was higher than 12.00 weeks. The highest age at inflection point estimated by von Bertalanffy in Nera Black chickens could be due to the fact that the breed is an exotic breed, which has undergone genetic improvement (Imouokhome and Ojogho, 2012). The weight at the inflection point, which is a product of time to the inflection point (Knížetová *et al*., 1991), is a crucial parameter that helps to determine when growth is increasing at an increasing rate or increasing at a decreasing rate. The result of this study is a representation of the estimated derivatives of other parameters in the model. All the models estimated the highest weight at the inflection point in Giriraja chicken followed by near black and FUNAAB Alpha chickens. What all these chickens have in common is the improved traits of growth at the high maturing rate to achieve the highest asymptotic weight. Von Bertalanffy estimated the highest weight at the inflection point for all the exotic breeds and crossbred chickens which is in agreement with findings of Ogunpaimo *et al*. (2020).

Based on the study, DIC selection criteria, von Bertalanffy growth model had the best fit for data recorded for all the breeds. This model ended up with the lowest DIC value and Kizilkaya *et al*. (2002, 2003) reported that the model with smallest DIC values is indicative of better data fit.

CONCLUSION

The results of this study showed that all the four growth models demonstrated capacities of fitting the growth of the studied breeds. However, von Bertalanffy reflected the real data well both at parameters level and the best fit criteria. At the point of inflection, i.e. the moment at which the animals' growth rate was the highest, the body weight of all breeds of chickens showed similar variation when fitted by the von Bertalanffy. Moreover, the logistic model estimated the highest growth rate slightly earlier than the von Bertalanffy function. Nonetheless, to predict the growth of the breeds considered in this study, von Bertalanffy model would be a better choice based on the information theory of deviance. These results will be a helpful tool for breeders in selecting the most profitable breeds.

AUTHOR'S CONTRIBUTIONS

Conceptualization: ABE, O. S., PETERS, S. O.
Methodology: ABE, O. S., OLANIYI, W. A., PETERS, S. O.
Investigation: ABE, O. S.
Data curation and supervision: PETERS, S. O., ABE, O. S.
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Project administration: ABE, O. S., PETERS, S. O., OZOJE, M. O.
All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY STATEMENT

The data presented in this study are available on request from the corresponding author.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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