

ASSESSMENT OF GROWTH PATTERN IN INDIGENOUS KADAKNATH CHICKENS BY NON-LINEAR MODELS

L. Gautam^{1*}

¹Department of Animal Genetics and Breeding, College of Veterinary & Animal Science, Navania, Udaipur-313601, Rajasthan University of Veterinary & Animal Sciences, Bikaner, Rajasthan, INDIA

*Corresponding author's email: lkgautam10@gmail.com

ORCID <https://orcid.org/0000-0001-6659-1366> Lokesh Gautam

ABSTRACT

Mathematical growth functions can explain the factors influencing an animal's growth pattern. However, there remains limited understanding of the growth curve of Kadaknath chickens, which is crucial for optimizing management and feeding practices. Therefore, this study aimed to determine the growth curve of indigenous Kadaknath chickens' body weight using four growth curve models: Logistic, Gompertz, Von Bertalanffy, and Richard. We analyzed 96 birds for this study. The models were fitted using Curve Expert and Minitab software, and we compared them based on Akaike's information, Bayesian information, adjusted R^2 , and RMSE criteria. The research revealed that the Gompertz and Richard models had higher coefficients of determination (R^2) and lower RMSE values in both sexes compared to other models. The age at the inflection point was estimated to be between 11 to 17.5 weeks for males and 9 to 11.4 weeks for females. According to the Richard model, adult male birds weighed 2157g, and females weighed 1297g. In the Gompertz model, male birds weighed 2186g, and females weighed 1468g. The inflection weight of birds in the Richard model was estimated to be 797.53g for males and 519.66g for females, while in the Gompertz model, it was 803.67g for males and 510g for females. In conclusion, our study determined that the Gompertz model is a reliable predictor of the body weight of male and female Kadaknath chickens from hatching to adulthood. The Richard model also demonstrated high reliability, albeit slightly behind the Gompertz model in predictive accuracy.

Key words: Body weight, growth pattern, Kadaknath, Non-linear models

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INTRODUCTION

Domestication of chickens (*Gallus gallus domesticus*) began around 9,900 B.C. (Sawai *et al.*, 2010), and today chickens are an important part of agriculture in many countries. Since chickens are India's principal source of eggs and meat, they provide a significant contribution to the country's agricultural output. The highly structured commercial sector of India's poultry industry accounts for over 80% of the market share, while the unorganized sector accounts for roughly 20%, as described by the country's National Action Plan, 2022. Backyard poultry, which is part of the unorganized sector, is an important way for the poor to earn extra money and feed their families. As per 19th Livestock Census estimates, There are around 30 million farmers who raise poultry in their backyards, and that there are 729 million chickens worldwide, with 30% being layers and 40% being broilers.

Kadaknath chickens are a special kind of indigenous chicken that are found in the Jhabua region of

Madhya Pradesh (MP), as well as in the neighboring areas of Gujarat and Rajasthan in the Indian state. This variety naturally adapted to the regional agroecosystem via generations of selective breeding. When compared to other exotic poultry breeds in their natural environment and when allowed to roam freely, the Kadaknath birds show a remarkable degree of resilience to disease. Poor housing, inept management, and inadequate nutrition are all things that the Kadaknath bird can tolerate (Thakur *et al.*, 2006). The Kadaknath breed is reputed to have aphrodisiac powers due to its high protein content (Rao and Thomus, 1984). The dark flesh, texture, taste, and flavor of the Kadaknath breed make it a famous indigenous breed of India. Black Meat Chickens come in three distinct varieties around the world. Kadaknath is from India, Silkie is from China, and Ayyam Cemani comes from Indonesia.

From birth to maturity, animal development involves a wide range of physiological and morphological processes. Chicken growth curve models often use a mathematical fit to empirical data on weight measurements taken at various stages of development. In

order to summarize the development of animals, scientists have turned to mathematical formulae and growth curves that yield numbers with biological meaning. The starting mass, growth rate, inflection point, and asymptotic mature weight can all be estimated with the use of these models for the growth curve. Researchers can use these growth curve models to get a quantitative read on the sizing and maturation traits of various chicken breeds, as well as the effects of various management strategies and diets on growth, the best time to slaughter, and the expected carcass weight. Professionals in the poultry industry may optimize production methods, create nutritious feeding plans, and boost output by analyzing growth patterns. The growth curves of livestock can be estimated using a variety of models, including the Brody, Bertalanffy, Gompertz, Logistic, Richards, and Weibull models (Ricklef, 1968). Estimating the growth curve model in Kadaknath chickens using the Logistic, Gompertz, Richard, and Bertalanffy models is important for developing a uniform method of managing this breed. Due to the scarcity of data on the growth curve of Kadaknath chickens, this research is crucial for knowing their development habits and pinpointing their hereditary potential.

MATERIALS AND METHODS

Location: The study involved 96 Kadaknath birds (48 males and 48 females) at the Livestock Farm Complex, College of Veterinary & Animal Science, Udaipur, Rajasthan University of Veterinary and Animal Sciences, Bikaner, India.

Experimental Housing and Feeding Management: Dark gravel covered the floor of the abandoned structure. The cages and troughs used in the experiment were cleaned, disinfected, and sprayed for external parasites before introducing the animals. The experimental chicks received identical care and management, and thorough sanitation measures were implemented throughout the trial period in accordance with regulations. On the day of hatch, the chicks were weighed, wing banded for simple

identification, and randomly allocated to brooding quarters. Body weights were assessed at weekly intervals from birth to 14 weeks of age for all 96 chickens, all of which survived from birth to 14 weeks of age. They were brooded and raised for 14 weeks on diets recommended by NRC, 1994 for chicks and growing pullets. The birds received the necessary immunizations and treatments according to the protocol. Local understanding of Kadaknath chicken growth inspired the decision to select chickens at 14 weeks of age. To prepare for the assessment of growth functions, we used the following linear model to assess the relevance of fixed factors, such as weeks, sex, and their interaction on body weight:

$$Y_{ijk} = \mu + T_i + S_j + T_i * S_j + e_{ij}$$

Where Y_{ijk} is the body weight at i^{th} week of the k^{th} animal with sex j^{th} , μ is the overall mean, T_i is the fixed effect of week i , S_j is the fixed effect of sex j , $T_i * S_j$ is the interaction between week i and sex j , and e_{ijk} is residual error. The model was fitted using Minitab software and the significant effects were stated at $p < 0.05$.

Growth function and estimates: The majority of the asymptotic and mechanistic mathematical functions that have been used for modeling the growth of chickens are ubiquitous. In these models, the variable that is the dependent one is assumed to have an asymptotic value as the independent variable approaches infinity, taking into account the physiological development of an organism. Although most of these growth models have a sigmoid structure and apply non-linear functions, the rates at which they grow might vary (Darmani Kuhl *et al.*, 2010; Narinc *et al.*, 2017).

The three-parameter Gompertz (Gompertz, 1825), Logistic (Pearl, 1977), and von Bertalanffy models as well as the four-parameter Richards (Richard and Kavanagh, 1945) functions are the non-linear regression models that are most frequently used to predict chicken growth. Table 1 shows the equations for the von Bertalanffy, Gompertz, Logistic, and Richards growth models as well as their coordinates for the point of inflection.

Table 1: Expression and point of inflection of commonly growth curve models used in this study (Goshu and Koya, 2013).

Model	Equations	Weight of inflection (W_i)	Time of inflection (T_i)
Logistic	$Y_t = \frac{A}{1 + Be^{-kt}}$	$A/2$	$\frac{1}{k} \log B$
Gompertz	$Y_t = Ae^{-B \exp(-kt)}$	A/e	$\frac{1}{k} \log B$
Richard	$Y_t = A(1 - Be^{-kt})^m$	$A \left[1 - \frac{1}{m}\right]^m$	$\frac{1}{k} \log[mB]$
Von Bertalanffy	$Y_t = A(1 - \beta e^{-kt})^3$	$(8/27)A$	$\frac{1}{k} \log(3B)$

Note: In the equation, Y_t body weight in g at the time t , A is the asymptotic weight in g (mature body weight the animal is assumed to be able to reach); B is the biological parameters about the shape of the curve (characterize the first part of growth before the point of inflection); k is the biological parameters about the maturing rate (g/week) (characterize the second part in which growth rate decreases until the animal reaches the asymptotic or mature weight A); m is the shape parameter (determine the position of the curve point inflection); e is the natural constant (2.72) and t is the time (week).

Table 2: Goodness-of-fit statistics:

The goodness-of-fit criteria used for non-linear regression equations are presented in Table 2 (Narinc *et al.*, 2017; Nguyen *et al.*, 2023).

Goodness-of-Fit Criteria	Formula
Coefficient of Determination	$R^2 = 1 - \left(\frac{SSE}{SST}\right)$
Adjusted R^2	$R_{ADJ}^2 = R^2 - \left[\left(\frac{k-1}{n-k}\right)(1-R^2)\right]$
Mean Square Error	$MSE = \frac{SSE}{n-k}$
Root Mean Square Error	$RMSE = \sqrt{\frac{[\sum_{i=1}^n (y_i - \hat{y})^2]}{n-k}}$
Akaike's Information Criterion	$AIC = n \cdot \ln\left(\frac{SSE}{n}\right) + 2k$
Bayesian Information Criterion	$BIC = n \cdot \ln\left(\frac{SSE}{n}\right) + k \cdot \ln(n)$

Note: SSE: sum of square errors; SST: total sum of squares; n : number of observations; k : the number of parameters; y_i : The actual (observed) value of the dependent variable. \hat{y}_i : The predicted value of the dependent variable. A growth curve with a high coefficient of determination (R^2) and a low MSE, RMSE, AIC and BIC value can be inferred to be accurate for predicting body weight from birth to maturity.

The growth curves of the Logistic, Gompertz, Richard and Bertalanffy models were derived male and female separately using Curve Expert 2.7.3, Minitab software and similar methods were applied for fitting the models.

RESULTS

The descriptive statistics for body weights at various ages (0 to 14 weeks) for males and females of Kadaknath chickens are shown in Tables 3. Males' body weight headed from 26.93g to 997.32g, and female weight increased from 25.39g to 891.83g. The findings of the linear model showed that sex, week, and their interactions significantly ($p < 0.05$) affected body weight. It had a low coefficient of variation. Across all age categories, the estimated least square means for male body weight were consistently higher than those for females. Further analysis was conducted using growth curve models, including the Logistic, Gompertz, Von Bertalanffy, and Richard models. Table 4 and Table 5

Goodness-of-Fit criteria: In some instances, the application of a model is not adequately supported, and in fact, a number of competing models may appear to match the data equally well. Therefore, it is important to understand the criteria that can be used to compare the degree of accuracy of fit of several competing models (Narinc *et al.*, 2010; Karadas *et al.*, 2017; Narinc *et al.*, 2017). The non-linear equations comparison using the goodness-of-fit criteria is shown in table 2.

present the growth curve parameters, calculated inflection point, and goodness-of-fit criteria for each model. These parameters were used to assess whether the models adequately described the relationship between age and body weight in growing Kadaknath chickens (both males and females). Figures 1 and 2 depict the estimated non-linear model growth pattern along with the curve of the observed body weights for male and female chickens, respectively.

Female Growth modeling: Gompertz and Richard models provided a better match for the data than logistic and Von Bertalanffy equations, according to a comparison of models based on the adjusted coefficient of determination (Adj. R^2) (99.55 and 99.52 vs. 99.40 and 99.44, respectively). The R^2 trend showed a similar pattern. To further support this conclusion, it is necessary to consider the MSE, RMSE, AIC, and BIC values. The Gompertz and Richard models had lower MSE and RMSE values as well as smaller AIC and BIC values, it indicated that these models have the best fitting to the observed body weight data. AIC and BIC were useful for

model selection, considering the trade-off between model complexity and goodness-of-fit. Lower AIC and BIC values indicate a better fit while penalizing overly complex models. The functions ranked based on AIC, the Gompertz model showed the smaller value followed by Richard, Bertalanffy and Logistic models. In this regards

Fig. 1, which supports these conclusions, it can be seen that the Gompertz and Richard model accurately described the growth pattern of female birds. In contrast, the logistic model slightly overestimated initial body weight and underestimated final body weight.

Table 3: The Average of body weight (g) and standard error in Kadaknath chickens.

Age (week)	Body weight (g) ± SE	
	Male (N=48)	Mean (N=48)
0	26.93±0.15	25.39±0.15
1	37.18±0.58	35.61±0.47
2	51.63±0.09	50.25±0.07
3	73.70±0.05	71.94±0.05
4	117.93±0.04	116.37±0.06
5	144.41±0.06	143.58±0.08
6	232.94±0.12	231.84±0.05
7	351.99±0.06	350.07±0.04
8	441.70±0.12	440.42±0.07
9	537.07±0.05	535.40±0.31
10	647.25±0.06	615.01±0.52
11	699.81±0.17	669.40±0.07
12	832.47±0.06	790.93±0.07
13	997.32±0.44	891.83±0.45

N: Number of birds, *Sex had significant effect (P≤0.05)

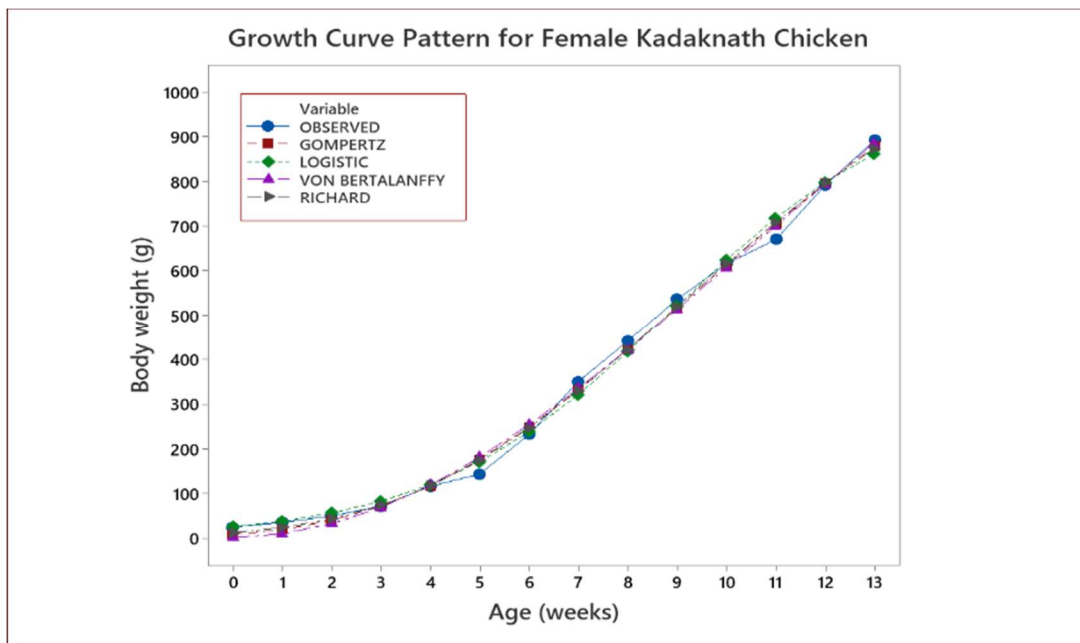


Fig. 2 Relationship female body weight with time (weeks)

Male Growth modeling: The results showed that Gompertz and Bertalanffy functions offer the best fit to the data based on R² and Adjusted R². Additionally, the Root Mean Square Error (RMSE) values for the Gompertz and Bertalanffy functions were nearly the same and lower (23.90 and 24.40), respectively) compared to

the Richard and logistic model (25.08 and 28.92). A lower RMSE value indicates that the Gompertz and Bertalanffy models' predictions are closer to the actual data points, suggesting that they provide a better fit to the observed growth patterns of male chickens. Furthermore, Gompertz had the lowest AIC when fitting the growth

equations, followed by Bertalanffy, Richard, and Logistic models. In contrast, the logistic model, while having the highest RMSE and higher AIC, also exhibited biases in its predictions for the overestimates of initial and underestimates of final body weights of male chickens. Fig. 2 visually showed that the Gompertz and Bertalanffy functions' predictions aligned well with the actual growth data for male birds, indicating that these models are reliable in describing the growth patterns observed in the dataset.

Inflection Point Traits: Table 4 presents the estimated weight and age at the inflection point. The age at the inflection point (T_i) indicates the period of highest growth rate of live weight over time. An inflection point is a location on a curve where the curvature shifts its direction. When considering growth patterns or other data curves, it typically signifies a transition from one phase to another.

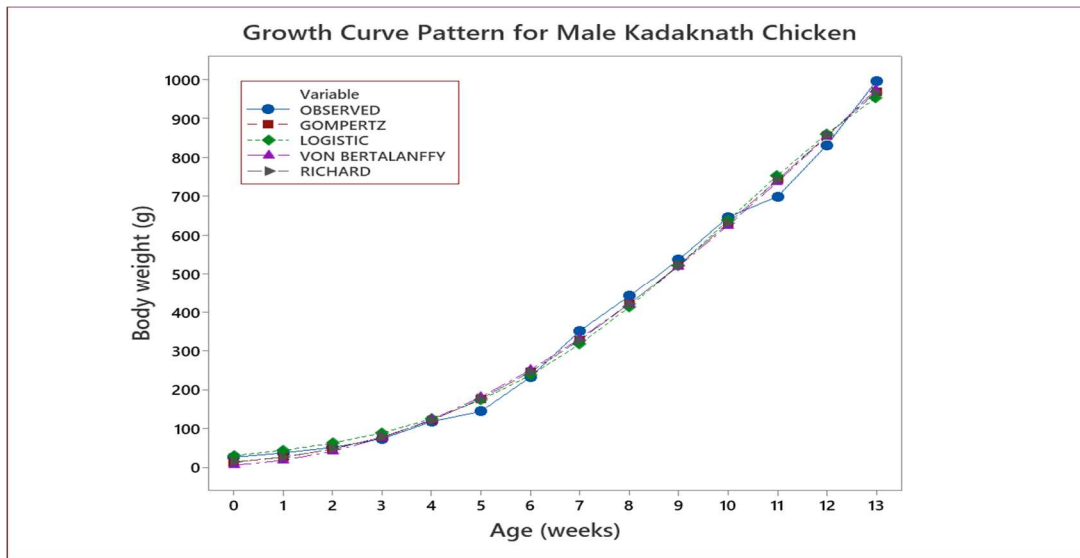


Fig. 1 Relationship male body weight with time (weeks)

T_i values obtained using the Gompertz model (4.04 and 3.36 week for male and female Kadaknath chickens, respectively) were lower than those estimated using the Bertalanffy, Richards and Gompertz functions, which were higher for both sexes. The weight at the inflection point (W_i) peaked when using the Bertalanffy function, reaching 1426 g for males and 650 g for females among Kadaknath chickens. Following this, similar trends were observed with the Gompertz, Richards, and Logistic models for both male and female chickens. It's worth noting that male chickens exhibited higher asymptotic weight and inflection point weight compared to females.

The logistic model yielded the lowest predicted asymptotic weight in male and female Kadaknath (1257 and 1020 g, respectively), whereas the Von Bertalanffy model yielded the greatest (4816 and 2194 g, respectively) (Table 5). Similar male maturation rates (k) (0.14) were found in the model by Gompertz and Richard. In both sexes, the logistic model yielded the highest results, while the Bertalanffy model yielded the lowest. Hens outgrew cocks in every simulation. The predicted female maturation rate (k) was 0.41, 0.18, 0.09, and 0.22 for the logistic, Gompertz, Von Bertalanffy, and Richard models, respectively (Table 4). There were also differences in the values of the constant (B) and the shape parameters (m) between the sexes and models.

Table 4: Estimated parameters for growth curve models in Kadaknath Chickens.

Model	Male						Female					
	A	B	K	m	T_i	W_i	A	B	K	m	T_i	W_i
Logistic	1257±117.10	58.39	0.37	-	11	628.50	1020±58.02	58.73	0.41	-	10	510.0
Gompertz	2186±437.81	1.76	0.14	-	12.57	803.68	1468±168.4	1.81	0.18	-	10.25	539.71
Bertalanffy	4816±2367.1	0.95	0.06	-	17.5	1426.96	2194±58.02	1	0.09	-	11.4	650.07
Richard	2157±1431.1	-0.05	0.14	-	11.6	797.53	1297±308.1	-1.44	0.22	-	9.0	519.66
					98.54						5.2	

A: the mature body weight (g); B: biological parameter about the shape of curve; k: maturing rate (g/week); t: age in week; m: shape parameter; W_i : weight of inflection (g); T_i : time of inflection (week).

Table 5: Goodness of fit of growth curve models for body weights in males and females in Kadaknath Chickens

Model	Male						Female					
	AIC	BIC	MSE	RMSE	R^2	Adj. R^2	AIC	BIC	MSE	RMSE	R^2	Adj. R^2
Logistic	96.83	98.74	836.09	28.92	99.33	99.21	90.88	92.80	546.88	23.39	99.49	99.40
Gompertz	91.49	93.41	571.30	23.90	99.55	99.46	86.91	88.83	411.88	20.29	99.62	99.55
Bertalanffy	92.14	94.06	598.46	24.40	99.52	99.43	89.80	91.72	506.25	22.50	99.53	99.44
Richard	93.51	96.06	628.94	25.08	99.54	99.40	88.47	91.03	439.02	20.95	99.63	99.52

Note: AIC: Akaike's information criterion; BIC: Bayesian information criterion; RMSE: Root mean square; R^2 : Coefficient of determination and Adjusted R^2 .

DISCUSSION

The Kadaknath breed holds significance in preserving India's indigenous genetic heritage due to its prized attributes, including the quality of its black meat, texture, and flavor. Despite its importance, there's a lack of available data on the breed's development and productivity. Various growth models have been explored to predict maximal growth rates, age, and eventual weight in animals (Selvaggi *et al.*, 2015; Narinc *et al.*, 2017; Meta-Estrada *et al.*, 2020). However, inconsistencies in model performance across research studies arise from differences in sample sizes, breeds studied, and methodological approaches. In this study, we utilized models proposed by Gompertz, Bertalanffy, Richards, and Verhulst to enhance the genetic characteristics of Kadaknath chickens.

Our findings revealed the Gompertz growth model as the most suitable for analyzing their development, exhibiting close alignment with live-weight data for both male and female chickens. Notably, the Gompertz equation requires fewer parameters compared to the Richards function. Studies by (Norris *et al.*, 2007; Rizzi *et al.*, 2013; Selvaggi *et al.*, 2015; Narinc *et al.*, 2017; Mata-Estrada *et al.*, 2020; Nguyen *et al.*, 2021; Ridho *et al.*, 2021; Mustafa *et al.*, 2022) support the use of the Gompertz growth curve for poultry growth analysis. However, discrepancies in its applicability may arise due to various factors such as breed variation, bird sex, feeding strategies, environmental conditions, sampling methods, and statistical considerations.

The observed traits, typical of slow-growing chicken breeds, are consistent with the growth metrics and trends observed in our study's sample population, as discussed earlier. Specifically, the estimated asymptotic weights (A) in our research closely mirror those documented for slow-growing populations (Ahmadi and Golian, 2008; Rizzi *et al.*, 2013; Selvaggi *et al.*, 2015). Employing the Gompertz model, male and female Kadaknath chickens demonstrated estimated weights of 2186 g and 1468 g, respectively, similar to the 2623 g and 1537 g recorded for male and female Mia chickens from Vietnam (Nguyen *et al.*, 2021). However, these values are substantially lower than those reported by

(Selvaggi *et al.*, 2015), which were 5661 g for females and 5870 g for males.

After the maximal growth rate, the parameter measures the maturation rate (k) or the growth speed to attain the asymptomatic weight. Researchers need to learn more about its biology in the future so that they can better predict the rate at which it will mature, which is crucial for informing farmers' management decisions (Nguyen *et al.*, 2021). Producers looking for animals with lower energy needs may find that early maturity and lower mature weight are beneficial, depending on their breeding and marketing goals. Females had a slightly higher value from the Gompertz model than males; these values were comparable to those found in the Chinese Yellow chicken (0.13 g/week for males; Yang *et al.*, 2006) and the Mia Chicken (0.15 g/week for females; Nguyen *et al.*, 2021).

In the context of growth curve modeling, the inflection point marks a significant transition where the growth rate changes direction, providing valuable insights into age and weight at puberty. Our study found that male Kadaknath chickens exhibited a higher mature body weight compared to females, which aligns with previous research findings (Norris *et al.*, 2007; Mata-Estrada *et al.*, 2020; Nguyen *et al.*, 2023). However, female Kadaknath chickens reached puberty earlier than males. Individuals reaching maximum weight at younger ages tend to achieve a lower mature body weight due to the inverse correlation between the rate of maturity and mature body weight.

The age and weight at the inflection point for Kadaknath chickens showed similar values to those reported for other indigenous chicken breeds (Miguel *et al.*, 2008; Rizzi *et al.*, 2013; Nguyen *et al.*, 2021). However, (Mustafa *et al.*, 2022) found that the logistic model estimated the time of inflection earlier compared to the Gompertz, Bertalanffy, and Brody models in Iraqi indigenous chickens. Given the rapid development typical in chickens, recent literature, including studies by (Sakomura *et al.*, 2011; Selvaggi *et al.*, 2015; Zhao *et al.*, 2015), reports a very low age at the inflection point.

Table 4 illustrates that, for Kadaknath chickens, the weight of inflection (Wi) constitutes 36.8% of the mature body weight according to the Gompertz model,

50% according to the Logistic model, and 29.6% according to the Von Bertalanffy model for both sexes. Moreover, it accounts for 37.1% and 40.1% according to the Richard model in males and females, respectively. These findings enhance our understanding of the feeding requirements for Kadaknath chickens. Due to the divergent growth rates between males and females, it is advisable to rear them separately and adjust the feed formulation at 12 weeks for males and 10 weeks for females, as per predictions from the Gompertz, Richard, and Logistic models. This recommendation is supported by the fact that the average body weight of males may be 46% higher than that of females. In addition, conserving local poultry populations is vital for enhancing poultry biodiversity. Research on endangered subpopulations, as noted by (Sossidou *et al.*, 2011; Thiruvenkadan *et al.*, 2011; Selvaggi *et al.*, 2015), not only helps understand "backyard chickens" within these communities but also offers valuable insights into conservation strategies for preserving genetic diversity within poultry breeds.

Conclusions: The study conducted a comprehensive analysis of Kadaknath chicken growth patterns up to 14 weeks, highlighting consistent weight gains with males slightly heavier than females. Our linear models confirmed that sex and week are significant factors influencing body weight. By employing various growth curve models, such as Logistic, Gompertz, Von Bertalanffy, and Richard models, the study found the Gompertz model to be most effective in predicting the maximum live weights, with males reaching 2186 grams and females 1468 grams. Moreover, the Gompertz model estimated maturation rates at 0.14 grams per week for males and 0.18 grams per week for females. These findings underscore the crucial role of accurate growth models in poultry management, recommending tailored feeding strategies and management practices for optimal growth potential. The study advocates for further research to deepen our understanding of Kadaknath chicken biology and enhance production practices in poultry farming.

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Data availability: All the data recorded during the current study are mentioned in the manuscript

Author contribution: The study's concept, design, manuscript and data analysis was carried out by Gautam L.

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Declarations

Ethics approval: The study was approved by the Institutional Animal Ethics Committee (IAEC), which was set up in accordance with order no. IAEC/RES/01/07. Ethics for treating animals with respect were strictly adhered to throughout the entire procedure.

Conflict of interests: The authors declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

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