COMPARISON OF NONLINEAR GROWTH MODELS OF NATIVE CHICKENS *(Gallus gallus domesticus* L., Atak-S) REARED IN ORGANIC PRODUCTION

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Abstract. This study aimed to compare the Logistic, Gompertz, and Von Von Bertalanffy growth models to determine which best fits the data for the native chicken (*Gallus gallus domesticus*, Atak-S) breed. A total of 120 male and 120 female Atak-S chicks were included, with weekly body weight data recorded from hatch to 18 weeks of age. Statistical analysis was performed using the SPSS version 15 program, incorporating three distinct models: Logistic (L), Gompertz (G), and Von Von Bertalanffy (V). The estimated asymptotic weights (A) of male chicks were 2365 ± 189.40 g for the Logistic model, 2999 ± 329.36 g for the Gompertz model, and 3684 ± 515.60 g for the Von Von Bertalanffy model. The corresponding growth rate (k) values were 0.22, 0.11, and 0.74 for the L, G, and B models, respectively. The Von Bertalanffy model outperformed the others with the lowest AIC (150.02) and BIC (156.24), indicating the best fit in terms of model selection criteria. It also demonstrated the lowest MSE (3139.60) and RMSE (56.08), signifying the smallest prediction error among the three models. The Von Bertalanffy model provided the most accurate and efficient fit for the data, with the highest R^2 (99.30) and adjusted R^2 (99.20) in Atak-S chicks.
Keywords: *Atak-s, body weight, growth curve, inflection point, mature weight*

Introduction

The Atak-S chicken *(Gallus gallus domesticus)* one of the free-range chicken breeds, has been developed specifically for Turkey's climate and conditions. It is highly preferred due to its adaptability to all types of climates, resistance to harsh poultry house conditions, and an average annual egg production of 260–290 eggs. Atak-S is the first locally developed commercial egg-laying chicken breed by the Poultry Research Institute (TAE).

In recent years, it has become the most popular breed in the free-range poultry sector. The main reason for this is its remarkable resistance to harsh climate conditions and potential diseases, compared to other breeds. The Atak-S chicken was created through the crossbreeding of the Rhode Island Red (RIR) and Plymouth Rock breeds. The "S" at the end of Atak-S refers to the black color of the Atak breed.

Body weight of local chickens (LC) is an important economic trait for farmers. This characteristic is heritable, and therefore, it could be improved through breeding programs (Osei-Amponsah et al., 2013).

Growth, measured as body mass or body weight (BW) over time, is often analyzed using mathematical equations fitted to growth curves. One key objective of curve fitting is to mathematically describe BW progression over time or age with biologically meaningful parameters. A clear understanding of these model parameters and their relationships serves as a foundation for developing breeding strategies to modify or optimize growth trajectories. Various nonlinear models have been used to describe growth curves in chickens (Aggrey, 2002).

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Growth is generally defined as the increase in size, number, or mass over time. However, it also encompasses the energy processes within the developing animal, including metabolism, nutrition, and genetics (Parks, 1982). Mathematical growth curves are employed to represent the development of an animal over the course of its life (Kocabaş et al., 1997; Bayram and Akbulut, 2009).

Growth functions or growth models explain biological information through growth curves and their parameters (Akbulut et al., 2004). The precise understanding of the growth curve is crucial as it impacts production efficiency (Fitzhugh, 1976). Predicting animal growth can be done by plotting age-weight graphs using mathematical models (Bathaei and Leory, 1996).

To develop an effective breeding strategy aimed at altering growth patterns, it is essential to have a deep understanding of the model parameters and their biological interactions. Several nonlinear models (NLM) have been used to describe growth curves in chickens, such as those proposed by Sang (1962), Grossman and Bohren (1982), and Grossman et al. (1985). While the logistic function has been applied to chicken growth data, its symmetric structure fails to accurately reflect the true growth pattern of chickens.

Throughout an animal's lifespan, it undergoes major physiological and morphological changes as it matures. Growth is generally defined as the increase in body weight and organ size over a given period or age (Yang et al., 2006; Kaplan and Gürcan, 2018).

Growth curve models play a crucial role in practical animal production management, aiding in decision-making and estimating daily nutrient requirements for optimal growth (Akbaş and Oguz, 1998). These estimates also allow for the calculation of total feed requirements (Ahmadi and Mottaghitalab, 2007).

Analyzing growth and development curves helps in understanding and predicting the dynamic patterns of an animal's growth (Grossman, 1985; Fan and Ye, 1997). Additionally, early growth patterns and genetic parameters are vital for effective early-stage breeding programs (Roush and Branton, 2005).

Among the most commonly used models for poultry growth curves are the Logistic, Gompertz, and Von Bertalanffy equations. The Gompertz growth function, known for representing a single sigmoidal growth phase, is widely applied in broiler growth data analysis (Wang and Zuidhof, 2004).

The objective of this study was to compare three nonlinear models (Logistic, Gompertz, and Von Bertalanffy) to describe the growth parameters of native chicken and determine the best model to define such parameters.

Material and methods

The study was conducted at the Poultry Research Center of Dicle University, Faculty of Agriculture (*Figure 1*) located in Diyarbakir Province, Turkiye (37°57'41 N and 40°13'54 E, 650 m a.s.l)

Animals and diets

Turkish native male and female layer ATAK- S chickens *(Gallus gallus domesticus*) (n=240) were used in the study. The one-day-old 120 male and 120 female chicks were housed in an organic free-range barn with a stocking density of 12 birds/m^2 in separate pens but in the same poultry house. The weight of the animals was measured every week from the first week to 18th of week. All weights were measured using a scale sensitive to 0.5 g.

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Figure 1. *Study location map*

Chicks were provided with ad libitum access to feed and water. The feeding program was divided into two phases: a starter diet (from hatching to 4 weeks of age) containing 19.0% crude protein (CP) and 3,000 kcal ME/kg, and a grower diet (from 5 to 18 weeks of age) containing 18.0% CP and 2,800 kcal ME/kg.

The ethical approval number is e-85181184-325.04.02-9482985, issued by the Provincial Directorate of Agriculture and Forestry in Diyarbakir under the Regulation on the Welfare and Protection of Animals.

Linear function

To assess the growth function, the following linear model (*Eq.1*) was applied to evaluate the impact of fixed factors including weeks, sex and their interaction on body weight.

$$\mathrm{Yijk} = \mu + \mathrm{Ti} + \mathrm{Sj} + (\mathrm{Ti} \times \mathrm{Sj}) + \mathrm{eijk} \qquad \text{(Eq.1)}$$

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_{jis} the interaction between week i and sex j, and e_{ijk} is residual error. The model was analyzed using Minitab software and effects were considered significant at $p<0.05$. Following the assessment of fixed effects using a linear model, nonlinear models were applied to describe and compare the overall growth trajectories of the chickens in more biologically meaningful terms.

Growth models

Three growth models were chosen to describe the growth pattern of native Atak-s: Logistic (L), Gompertz (G) and Von Von Bertalanffy (V)

Logistic model

To estimate the expected BW at specific age the following equation (*Eq.2*) describes the logistic growth model:

$$Wt = W_A/[1+\exp-K(t-ti)] \qquad \text{(Eq.2)}$$

where; Wt is the BW of the chicken at time t, W_A is the asymptotic BW (g), k is the exponential growth rate (g/day), ti is the age at which maximum growth occurs (days) (Robertson, 1923; Aggrey, 2002).

Gompertz

The following equation (*Eq.3*) describes the Gompertz growth curve:

$$W_t=W_0 \exp [(L/K) (1-\exp-Kt)] \quad \text{(Eq.3)}$$

where; Wt is the BW of chicken at time *t*, W_0 is the hatching BW (g), expis the exponential, *L* is the initial growth rate (g/D), and *K* is exponential growth rate (g/D).

Age of maximum growth (*ti*) (D) and asymptotic weight (WA) (g) were estimated as follows: ti=(1/K)log(L/k) and WA=W_0exp(L/K) (Laird et al., 1965; Aggrey, 2002).

Von Bertalanffy model

The Von Von Bertalanffy model has been used to describe the growth of indigenous chicken (Yang et al., 2006; Adenaike et al., 2017) using the equation (*Eq.4*):

$$W_t = W_A*(1-B*\exp(-K*t))^3 \quad \text{(Eq.4)}$$

where; Wt is the BW of chicken at time *t*, WA is the asymptotic BW (g), expis the exponential, *K* is the maximum relative growth (g/D), and *B* is the integration constant. Age of maximum growth (*ti*) (D) and BW at age of maximum growth (WI) (g) were estimated as follows: ti=ln(3B)/k and WI=WA∗8/27 (Goshu and Koya, 2013).

Statistical analysis

Three growth models Gompertz, Logistic and Von Bertalanffy were evaluated to determine the best fit for describing the growth patterns of native Layer chickens raised organically, with separate analyses conducted for each sex. A Chi-square test was performed on the growth data of each of the 240 chickens. All statistical analyses were conducted using Minitab Statistical Software (version 17) and SPSS (version 15.0, SPSS Inc., Chicago, IL, USA). Nonlinear regression was carried out using the Levenberg–Marquardt algorithm (Marquardt, 1963). The Chi-square test was used to assess the fit of each nonlinear growth curve to individual chicken data. A growth curve was considered an adequate fit if the calculated Chi-square statistic was less than or equal to the critical value at the 0.05 significance level ($\chi^2(17) = 27.59$, df = number of time points − number of parameters). Additional goodness-of-fit measures were derived from ANOVA generated through nonlinear regression analysis. These calculations utilized the nonlinear regression capabilities of SPSS 15.0 (Inc. Chicago IL. USA).

Goodness-of-Fit criteria

The models were compared based on three criteria to evaluate their goodness of fit (*Table 1*).

The objective of the current study was to compare average growth curves with the mean of individual growth curves in organically raised layer genotype. A further objective was to determine whether the Gompertz, Logistic or Von Bertalanffy model provided a superior fit to the growth curves observed in native layer genotype.

The optimal model was determined by the lowest RMSE, AIC and BIC values along with the highest adjusted coefficient of determination (R^2) (Narinc et al., 2013).

Table 1. *The goodness-of-fit criteria for nonlinear regression equations*

Criteria	Abbrev.	Equation
Coefficient determination	R^2	1−(SSE/SST)
Adjusted determination coefficient	Adj. R^2	R^2−[(k−1/n−k)(1−R2)]
Mean Square Error	MSE	SSE/ (n−k)
Akaike' information criterion	AIC	n∗ln(SSE/n)+2k; and
Bayesian information criterion	BIC	n∗ln(SSE/n)+k∗ln(n)

SSE represents the sum of squared errors, SST denotes the total sum of squares, n is the total number of observations, k refers to the number of parameters, and ln indicates the natural logarithm

Results

The descriptive statistics for body weights at various ages (0 to 18 weeks) for males and females of Atak-Schickens was shown in *Table 2*.

Table 2. *Means and standard error for body weight at different ages of Atak-s chickens**

Age (week)	Body Weight (g)	
	Male (N=120)	Female (N=120)
Hatch	39.20 ±1.22	36.25±1.02
1	95.24 ±1.44	62.46±1.18
2	195.12 ±1.52	101.94±1.38
3	360.58 ±2.22	172.66±1.54
4	480.44 ±5.68	249.22±1.86
5	558.36 ±5.80	351.24±2.02
6	672.12 ±8.87	449.92±4.85
7	753.86 ±10.22	557.04±5.76
8	896.42 ±11.97	630.34±7.43
9	1080.04 ±12.49	742.92±9.86
10	1140.64 ±14.45	812.46±10.41
11	1200.36 ±16.14	877.44±10.65
12	1304.24 ±18.10	1014.24±11.26
13	1400.18 ±21.95	1131.50±13.92
14	1540.52 ±23.27	1212.95±15.78
15	1642.34 ±24.51	1285.34±16.02
16	1800.20 ±32.69	1338.74±17.40
17	1964.18 ±37.43	1444.86±20.32
18	2088.40 ±39.75	1625.02±23.63

*Sex had significant effect ($P \leq 0.05$)

At hatch, males (39.20 g) are slightly heavier than females (36.25 g) indicating a natural sexual dimorphism in body weight from the start. Males consistently gain more weight than females throughout the 18-week period. By Week 2, males (195.12 g) are almost twice as heavy as females (101.94 g). This trend continues till with males maintaining a higher body weight. Both sexes show rapid weight gain from weeks 3 to 10. Males increase from 360.58 g (Week 3) to 1140.64 g (Week 10). Females follow a similar pattern but with lower weights, reaching 812.46 g at Week 10. At Week 18, males achieve 2088.40 g, whereas females reach 1625.02 g, a final difference of 463.38 g. This

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confirms that males maintain a higher growth potential in the study period. A linear model analysis revealed a significant impact of sex, week and their combined effect on body weight($p<0.05$).

A low coefficient of variation was observed in body weight. Estimated least square means showed that males had consistently higher body weights than females at all ages. Further analysis explored these differences using Logistic, Gompertz and Von Bertalanffy growth curve models (*Table 3*).

Table 3. *Estimated Parameters for growth curve in Atak-S chicks*

Model	Male (n=120)					Female (n=120)				
	A	B	k	Ti	Wi	A	B	k	Ti	Wi
L	2365± 189.40	11.22	0.22	10.99	1182.50	1729± 92.18	15.77	0.26	10.61	864.50
G	2999± 329.36	3.087	0.11	10.25	1103.27	2185± 148.68	3.58	0.12	10.63	803.82
V	3684± 515.60	0.691	0.74	0.5	2005.32	2702± 234.29	0.75	0.83	0.35	1470.78

L: Logistic; G (Gompertz); V (Von Bertalanffy) A: the mature body weight (g); B: biological parameter about the shape of curve; k: maturing rate (g/week); t: age in week; Wi: weight of inflection (g); Ti: time of inflection (week)

The growth curve pattern for male and female Atak-S chickens over a period of 18 weeks comparing observed body weights with those predicted by three different growth models was shown in *Figure 2*.

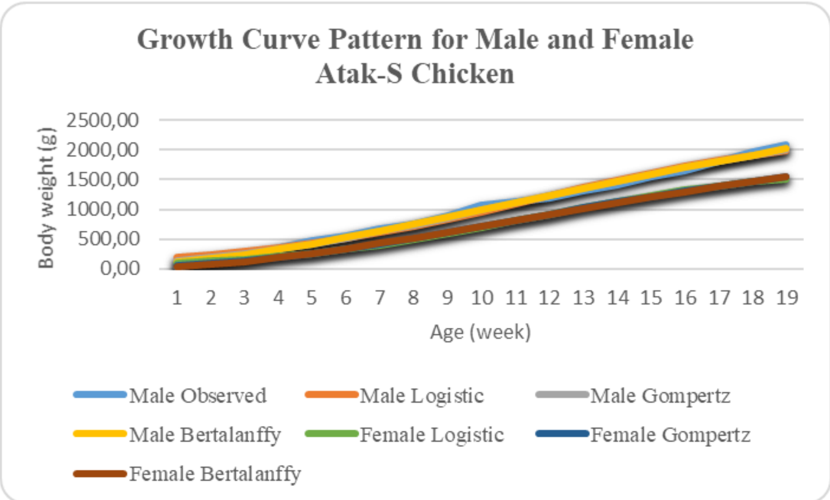

Figure 2. *Estimation of growth parameters using a nonlinear models on Atak –S chicken under the organic system*

The growth performance of Atak-S chickens follows a sigmoidal trend, with males achieving higher mature weights than females. The Von Bertalanffy model provides the most accurate prediction of observed growth making it the most suitable for modeling long-term weight development in this breed.

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Male growth modeling

The estimated asymptotic weights (A) of male chicks were 2365 ± 189.40 g for the Logistic model, 2999 ± 329.36 g for the Gompertz model and 3684 ± 515.60 g for the Von Bertalanffy model. The corresponding growth rate (k) values were 0.22, 0.11 and 0.74 for L, G and V model respectievly as it shown in *Table 3*. These results suggest that for the male chicks the Von Bertalanffy model best describes rapid growth and a higher mature weight compared to the other models (*Figure 3*).

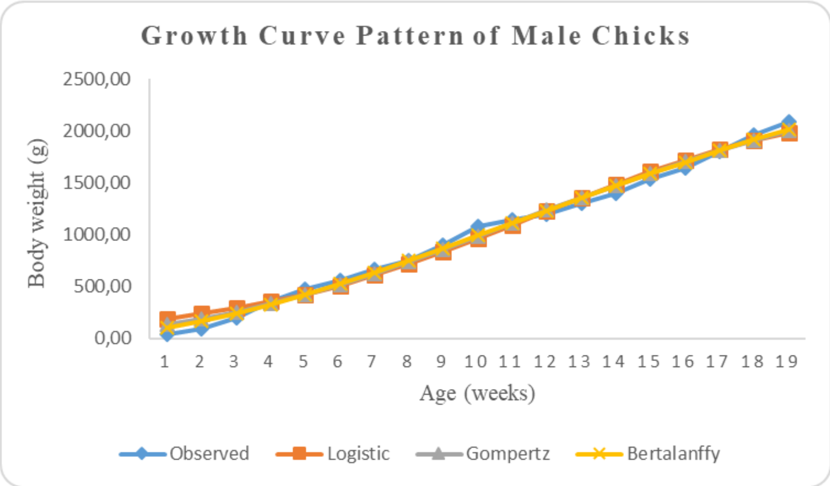

Figure 3. *Relationship male body weight with time (weeks) on Atak –S chicken under the organic system*

According to the the comparison of the models for male chicks was shown in *Table 4*.

Table 4. *Goodness of fit for growth curve models of body weight in M and F Atak-S chicks*

Model	AIC	BIC	MSE	RMSE	R^2	Adj R^2
Male						
Logistic	318.02	321.00	7451.39	86.34	98.30	98.00
Gompertz	168.54	171.53	4230.58	65.02	99.10	99.00
VonVon Bertalanffy	**150.02**	**156.24**	**3139.60**	**56.08**	**99.30**	**99.20**
Female						
Logistic	160.57	163.56	2840.91	53.32	99.00	98.80
Gompertz	130.54	136.14	1273.84	35.74	99.60	99.50
Von Von Bertalanffy	**124.24**	**129.83**	**886.62**	**29.78**	**99.70**	**99.60**

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

The Logistic model exhibits relatively higher values for both AIC (318.02) and BIC (321.00), indicating a suboptimal fit when compared to the other models. Additionally, the model's MSE (7451.39) and RMSE (86.34) are higher, suggesting a greater degree of prediction error. While the model provides a good fit with an R^2 of 98.30 and an adjusted R^2 of 98.00, these values are surpassed by the other models. The Gompertz model shows

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a significant improvement with lower AIC (168.54) and BIC (171.53), which suggest better model fit and a more favorable balance between model complexity and goodness-of-fit. Its MSE (4230.58) and RMSE (65.02) are lower than those of the Logistic model indicating superior predictive accuracy. The R^2 of 99.10 and the adjusted R^2 of 99.00 reflect an excellent fit, although it still lags slightly behind the Von Bertalanffy model in terms of model quality. The Von Bertalanffy model outperforms the others with the lowest AIC (150.02) and BIC (156.24) indicating the best fit in terms of model selection criteria. It also demonstrates the lowest MSE (3139.60) and RMSE (56.08), signifying the smallest prediction error among the three models. With the highest R^2 (99.30) and adjusted R^2 (99.20), the Von Bertalanffy model provides the most accurate and efficient fit for the data. The Von Bertalanffy model is the most optimal choice for modeling male chicks as it achieves the best balance between model fit, predictive accuracy and explained variance.

Female growth modeling

The estimated asymptotic weights (A) of female chicks were 1729 ± 92.18 g for the Logistic model, 2185 ± 148.68 g for the Gompertz model and 2702 ± 234.29 g for the Von Bertalanffy model. The corresponding growth rate (k) values were 0.26, 0.12 and 0.83 for L, G and B model, respectively (*Table 3*). The Von Bertalanffy model aligns best with higher growth rates and long-term weight gain, making it ideal for estimating final mature weights. the Von Bertalanffy model appears to provide the best fit for describing the growth of female Atak-S chicks over the study period (*Figure 4*).

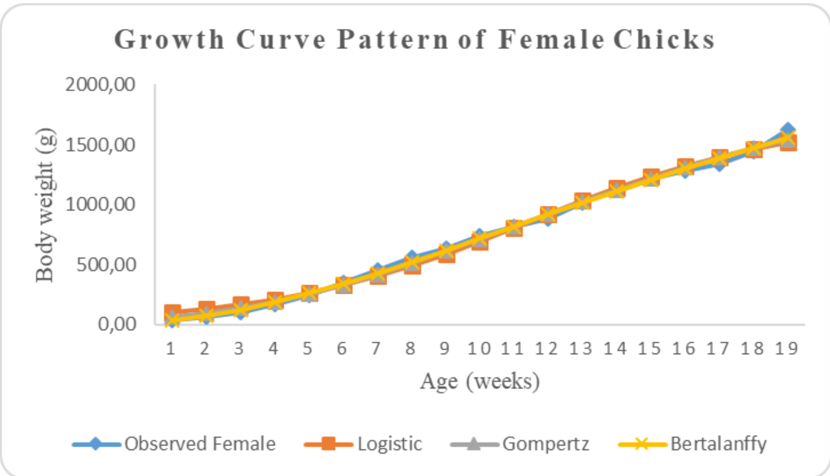

Figure 4. *Relationship female body weight with time (weeks) on Atak –S chicken under the organic system*

According to Goodness of fit for growth curve models for female chicks shown in *Table 4* Logistic model demonstrates relatively higher values for AIC (160.57) and BIC (163.56), suggesting a less optimal fit compared to the other models. Additionally, its MSE (2840.91) and RMSE (53.32) are higher, indicating greater prediction error. While the model provides a good fit with an R^2 of 99.00 and an adjusted R^2 of 98.80, these values are exceeded by the other models. The Gompertz model shows notable improvement, with lower AIC (130.54) and BIC (136.14), indicating a better model fit and a more favorable trade-off between complexity and performance. Its MSE (1273.84) and RMSE

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(35.74) are lower than those of the Logistic model demonstrating superior predictive accuracy. The R^2 of 99.60 and adjusted R^2 of 99.50 reflect an excellent fit, though it remains slightly behind the Von Bertalanffy model in overall model performance. The Von Bertalanffy model outperforms the others as indicated by the lowest AIC (124.24) and BIC (129.83), suggesting the best fit among the models. It also has the lowest MSE (886.62) and RMSE (29.78), indicating the smallest prediction error. Moreover, the R^2 of 99.70 and adjusted R^2 of 99.60 confirm its superior ability to explain variance in the data. The Von Bertalanffy model is the most suitable choice for modeling female chicks as it provides the best balance between model fit predictive accuracy and explained variance.

Discussion

Our findings indicated that the Von Bertalanffy model was the most appropriate for analyzing growth patterns as it closely matched the live-weight data for both male and female chickens. This conclusion is based on the best selection criteria, including the smallest RMSE, AIC, and BIC values, as well as the highest adjusted coefficient of determination (R^2). Several studies (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; Al-Ali et al., 2022; Gautam, 2024) have supported the Gompertz model as the preferred growth curve for poultry growth analysis. The Gompertz model is widely recognized for its biological interpretability and ability to describe the sigmoidal growth pattern of poultry with high accuracy. However, our findings suggest that the Von Bertalanffy model provides a better fit for the growth data of Atak-S chickens.

The superiority of the Von Bertalanffy model in this study can be attributed to its greater flexibility in capturing long-term growth dynamics. Unlike the Gompertz model which often emphasizes the early and middle growth phases, the Von Bertalanffy model accounts for prolonged growth and better represents the final stages of body weight gain. This is particularly important for breeds with extended growth periods or different genetic potential.

These differences highlight the importance of breed-specific evaluations when selecting an appropriate growth model. While the Gompertz model has been widely used for various poultry species, the results of this study suggest that the Von Bertalanffy model may be more suitable for Atak-S chickens, offering better predictive accuracy and improved biological representation of their growth trajectory.

The *k* value in these models represents the growth rate constant which a crucial parameter in growth models used to describe animal growth patterns. Examining the *k* values across the different models (L, G, and B) for both male and female animals provides insight into growth dynamics. In the Logistic model, *k* represents the relative growth rate. The female group has a slightly higher *k* value than males (0.26 vs. 0.22) suggesting that females reach their inflection point faster and have a relatively quicker growth rate compared to males. However, the asymptotic weight (*Wi*) of females is lower than that of males indicating smaller mature body weight. The Gompertz model assumes a more gradual approach to the asymptote. Here, *k* values are lower than in the Logistic model, meaning the growth rate is slower but more prolonged. Again, females show a slightly higher *k* value than males (0.12 vs. 0.11) which is consistent with the trend in the Logistic model. The Von Bertalanffy model typically describes growth over a longer timeframe with a declining growth rate after the initial phase. The *k* values here are significantly higher compared to the other models which aligns with the model's nature.

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Von Bertalanffy generally exhibits the lowest biological accuracy for early growth periods but provides a good fit for mature weight estimation. Females again have a higher *k* (0.83 vs. 0.74), reinforcing the trend of faster relative growth rates in females.

In all three models, the *k* values are slightly higher in females than in males suggesting that females tend to reach their mature weight at a slightly faster rate. These findings are consistent with the several studies reported for 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).

These trends indicate that while females grow at a relatively faster rate, males tend to attain a higher final body weight. The choice of model depends on the growth phase of interest Logistic for earlier growth, Gompertz for intermediate and Von Bertalanffy for overall long-term growth patterns.

Table 3 illustrates that the weight at the inflection point (Wi) for Atak-S chickens constitutes 49.9% of the mature body weight according to the Logistic model, 36.77% according to the Gompertz model, and 54.42% according to the Von Bertalanffy model for both sexes. These findings can be compared with the results reported by Gautam (2024) for Kadaknath chickens, where the Wi was 50% of the mature body weight for the Logistic model, 36.8% for the Gompertz model and 29.6% for the Von Bertalanffy model in both sexes. The differences in Wi percentages between Atak-S and Kadaknath chickens suggest variations in growth patterns between these breeds. While the Logistic and Gompertz models yielded similar Wi percentages for both breeds, the Von Bertalanffy model showed a notable difference, with Atak-S chickens reaching a higher proportion of their mature body weight at the inflection point compared to Kadaknath chickens (54.42% vs. 29.6%). This indicates that Atak-S chickens exhibit a different growth trajectory possibly influenced by genetic factors, breed characteristics or environmental conditions.

Conclusion

The analysis of growth models (Logistic, Gompertz, and Von Bertalanffy) revealed notable differences in growth parameters between male and female Atak-S chickens. Across all three models, the growth rate constant (k) was consistently higher in females than in males, indicating that females reach their mature weight more quickly. Among the models, the Von Bertalanffy model showed the most pronounced difference in k values between sexes, suggesting that it better captures long-term growth dynamics. The Logistic model exhibited a moderate difference, while the Gompertz model showed the least variation between sexes. Additionally, males exhibited higher asymptotic weights (A) across all models, confirming their greater mature body weight. These results suggest that while males grow over a longer period before reaching maturity, females tend to grow at a faster rate but attain a lower final weight. According to the result the Von Bertalanffy model provided the most accurate and biologically appropriate fit for both sexes, as demonstrated by its lowest RMSE, AIC, and BIC values and highest adjusted R^2. These findings have practical implications for breed-specific management and feeding strategies in organic poultry systems. The superior performance of the Von Bertalanffy model also highlights its potential utility in future genetic selection and growth optimization programs for native chicken genotypes such as Atak-S.

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Conflicts of interest. The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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