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A Comprehensive and Pioneering Application of 19 Non-Linear Models for Characterizing Growth Dynamics of Dual-Purpose Marandi Chickens

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Abstract

Growth curve parameters (GCPs) are essential for predicting body weight, optimizing nutrition, and improving production efficiency in poultry. The Marandi chicken, an indigenous Iranian laying breed ("Azerbaijan Black"), has high genetic potential for egg production but remains understudied, with its growth trajectory not yet fully characterized. In this study, we rigorously judged and compared 19 non-linear growth functions ten three-parameter (Brody, Gauss, Gompertz, Logistic, Lundqvist-Korf, Negative Exponential, Verhulst, Von-Bertalanffy, Weibull) and nine four-parameter (Blumberg, Bridges, Gompertz, Janochek, Logistic, Lopez, Morgan-Mercer-Flodin (MMF), Richards, Weibull) to identify the most appropriate model describing the weight-age relationship in this breed. Weight records from 305 chicks across two flocks were fitted using the NLIN procedure in SAS, and model selection was based on Akaike's Information Criterion corrected for sample size (AICc). After judging all candidate models, the Morgan-Mercer-Flodin (4P) was selected as among the best-fitting for Marandi hens (AICc = 18894.19 and 8880.44 for flocks 1 and 2, respectively), while the Bridges (4P) ranked top for Marandi roosters (AICc = 8936.98 and 5617.08). Among the three-parameter models, the Gompertz (3P) consistently emerged as the most appropriate alternative across all genetic groups (AICc: 8882.97–8957.24). Estimated asymptotic weights ranged from ~1730 to 2430 g, with roosters achieving higher mature weights than hens. This comparative judgment reveals that selecting the optimal growth function is a critical preliminary step in designing effective breeding strategies. Given the heritability of GCPs, our findings provide a foundational basis for enhancing Marandi chicken breeding programs through targeted genetic selection and sex-specific management.

Introduction

The growth process in poultry is dynamic and genetically programmed, significantly influenced by both genetic and environmental factors (Posada *et al*., 2014; Nawaz *et al*., 2025). Body weight is a crucial trait in livestock and poultry breeding, exhibiting moderate to high heritability, making it amenable to improvement through well-designed breeding programs (Kaplan & Gurcan, 2016; Yang *et al*., 2006). To understand the complex biological processes in living organisms, non-linear growth models are essential (Rodic *et al*., 2011). These

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models quantify growth parameters using mathematical equations (Aggrey, 2003; Yang *et al*., 2006). Growth curves help illustrate changes in an animal's body weight at specific ages. Although generally similar in overall shape, growth curves highlight subtle differences among species, breeds, and sexes. In poultry, the growth curve typically exhibits three phases: an initial rapid growth phase commencing from hatch, an inflection point (IP) indicating maximum growth rate, and an asymptotic or limiting point indicating the onset of maturity (Boonkum *et al*., 2021).

By leveraging Growth Curve Parameters (GCPs), researchers can accurately predict a bird's nutritional requirements and its ultimate achievable weight (Darmani Kuhi *et al*., 2003; Roush *et al*., 2006; Wen *et al*., 2019). Furthermore, optimizing environmental conditions and management practices can significantly enhance growth performance in poultry. The derivation of GCPs from non-linear regression functions facilitates the development of novel selection indices to achieve the most desirable growth pattern. By selecting animals based on GCPs and refining growth rates, the overall shape and characteristics of the growth curve can be modified (Koushandeh *et al*., 2019). In response to increasing demand for animal protein, the establishment of robust growth curve models has profoundly contributed to the genetic improvement of performance traits in livestock (Abbas *et al*.., 2014; Xie *et al.*, 2020) Various non-linear regression models, including Gompertz, Logistic, Richards, Weibull, and Von Bertalanffy, can be applied to predict poultry growth (Setiaji *et al*., 2023; Loengbudnark *et al*., 2025). Each of these models possesses unique characteristics, strengths, and limitations (Şengül *et al*., 2024). Non-linear regression models are generally categorized into two main groups in growth curve research: three-parameter and four-parameter models, often referred to as three-phase and four-phase models, respectively (Osaiyuwu *et al*., 2024). Various statistical criteria are employed to evaluate and select the most suitable model for animals, elucidating their growth characteristics across different poultry species, strains, and lines (Narinc *et al*., 2010; Şengül *et al*., 2024). Dual-purpose breeds are not a monolithic category; they include both egg-meat types (e.g., Marans, Ixworth) selected for table qualities and egg production, and egg-fancy or ornamental types (e.g., certain native breeds like the Iranian Marandi) maintained for exhibition or traditional purposes while still producing eggs. The growth patterns of fancy-type dual-purpose breeds often differ from those of production-oriented dual-purpose breeds, particularly in parameters such as growth rate and age at inflection point.(Sutherland *et al*., 2018) As a result, model selection based on information criteria like AIC becomes essential when comparing growth trajectories across these diverse dual-purpose categories, especially since sex-specific dimorphism further complicates the ranking of candidate growth functions (Bondoc, 2021; Becker & Büscher., 2023).

Indigenous chickens play a vital role in both commercial and non-commercial poultry industries, serving as invaluable genetic reservoirs with strategic importance for any country. They provide essential white meat and brown eggs to smaller communities (Chomchuen *et al*., 2022). The Marandi chicken, also known as the "Azerbaijan Black" chicken, is a distinctive breed recognized for its unique physical characteristics and excellent laying performance. Its body is covered in black feathers that exhibit a dark green iridescence under sunlight. The shanks are heavily feathered, and skin color varies from black to yellow, with gray-skinned birds being more prevalent. Roosters possess a single comb without wattles and a short beak, combining cream and black hues. Their striking red eyes are complemented by red earlobes, while hens feature white earlobes. Additionally, the toenails of Marandi chickens display a combination of black, yellow, and white colors, often highlighted by a creamy tone. Esteemed for both its egg production and ornamental value, the Marandi breed holds a special place within Iran's poultry community. This indigenous dual-purpose breed originates from the Azerbaijan region of Iran and demonstrates remarkable egg-laying capabilities that meet the needs of small rural communities. It is well-adapted to its native environmental conditions, exhibiting resilience against common poultry diseases and harsh, cold winters. Despite these strengths, limited information is available regarding its production and growth potential.

By selecting an ideal non-linear growth model for the growth pattern and accurately assessing its GCPs in indigenous poultry, a fundamental and appropriate breeding plan and strategy can be established, considering the breed's specific characteristics (e.g., layer, broiler, ornamental). This is crucial because

these GCPs, while part of a mathematical function, are real-world, changeable, and heritable traits in growth. Improving production efficiency through selection based on GCPs is often more effective than selecting for body weight alone. This is because modifying the curve shape, particularly concerning asymptotic weight (A) and maturity rate (k) parameters, is more straightforward (Saghi *et al*., 2022). Karaman *et al*. (2013) and Kumar *et al*. (2022) identified that determining the inflection point of the growth curve is a critical aspect of growth curve evaluation, particularly when a non-linear growth curve model is applied. This allows for the assessment of age and weight at inflection and the prediction of maximum weight or growth rate of the birds.

Marandi chickens are selectively bred alongside breeds such as Golpayegani, Mazandarani, Khazak, Brahma, Marans, Polish, and others in various villages and small towns across Iran. Typically, these breeding practices are conducted on a limited scale, often involving flocks of fewer than 50 chickens. Farmers usually raise birds near their crops, which can lead to unintentional intermixing between different breeds.

Several studies have applied nonlinear growth models to dual-purpose chickens, including Funaab Alpha (Durosaro *et al*., 2021), Denizli (Manav *et al*., 2026), and Ixworth (Becker & Büscher, 2023). However, all previous studies have tested a limited number of candidate models (typically 4–6) on a single population. The present study differs fundamentally in three ways: (i) we compare 19 nonlinear growth models, the most comprehensive model set ever tested in poultry growth research; (ii) we analyze two separate flocks of the indigenous Marandi breed; and (iii) we include both sexes (males and females) across two utility types (egg-laying and ornamental). To our knowledge, no previous study has applied such a large model set (19 models) to characterize growth in a native dual-purpose breed, enabling a more rigorous model selection using AIC across multiple subgroups. Unlike three-parameter models (Gompertz, Logistic) that fix the inflection point at a predetermined percentage of mature weight (36.8% and 50%, respectively), four-parameter models (Richards, MMF, Bridges) estimate the inflection point freely from the data. This flexibility makes four-parameter models inherently more suitable for dual-purpose indigenous breeds with variable growth patterns (Morgan *et al*., 1975; Sharifi *et al*., 2022).

To our knowledge, no prior research has evaluated nonlinear growth models for Marandi chicken growth data. Therefore, the present study aims to evaluate and compare the performance of 19 nonlinear growth models (ten three-parameter and nine four-parameter) for analyzing the growth curve of indigenous Marandi chickens across two flocks, both sexes, and two utility types (egg-laying and ornamental).

Materials and Methods

Birds and Farms Under Study

To investigate the growth curve characteristics of Marandi chickens, a total of 690 fertile eggs were sourced from Marandi flocks across five distinct regions in Northwestern Iran (Azarshahr, Osku, Urmia, Gowgan, and Marand) as well as from Karaj, located near Tehran, in 2023, and subsequently raised until 2024. Parental male and female birds were meticulously examined, and collected eggs were assigned to a hybrid group if a maximum of one parent was of a non-Marandi breed. The fertile eggs were incubated in two separate batches, leading to the formation of two distinct hatches. An overall hatching success rate of 62% yielded 426 one-day-old chicks, which were then transferred to the Khalat Pooshan Agricultural Research Station, University of Tabriz. Upon arrival, wing bands were attached to the chicks for the purpose of future trait recording.

The studied flocks comprised 181 Marandi hens and 124 Marandi roosters. The categorized groups are hereafter referred to as Marandi Hens flock1 (M-H-1) with 120 birds, Marandi Hens flock 2 (M-H-2) with 61 birds, Marandi Roosters flock 1 (M-R-1) with 70 birds, and Marandi Roosters flock 2 (M-R-2) with 54 birds.

Up to 14 weeks of age, chickens were reared on litter. At 15 weeks, female birds were moved to individual laying cages, while roosters continued to be housed on litter. Throughout the rearing period, a specific lighting program was implemented for the flocks. In adherence to hygiene principles and animal welfare standards, chickens received six vaccinations at various ages. As the birds matured, different dietary regimens were provided based on body weight and future requirements, following NRC (National Research Council) guidelines for Hy-line Brown W-98 laying hens (Table 1). Only the diet at 20 weeks of age (1300-1450 g; onset of lay) is reported here. Daily feed allocation was 100 g for roosters and 80 g for hens.

Chicks were weighed weekly or bi-weekly using a digital scale at the following ages: 1, 7, 14, 21, 28, 35, 49, 63, 77, 91, 105, 119, 133, 147, 161, 189, and 203 days for flock 2; and 2, 9, 16, 23, 30, 44, 58, 72, 86, 100, 114, 128, 142, 156, 184, and 198 days for flock 1. A general linear model (GLM) was used using SAS software to initially assess potential differences in growth patterns between hens, Marandi roosters, and their two flocks.

Handling of Missing Data and Bird Attrition

Initial counts: M-H-1=120, M-R-1=70, M-H-2=61, M-R-2=54 (total=305). At end of rearing (189 days): M-H-1=115, M-R-1=68, M-H-2=58, M-R-2=48 (total=289). Total attrition (sales + mortality) = 16 birds (5.2%). No birds were excluded due to missing records. For isolated missing values (1–2 time points), no imputation was performed; PROC NLIN accommodates unbalanced data.

Non-linear Growth Curve Models

To estimate the GCPs using non-linear regression in SAS software (version 9.4, 2017), the NLIN procedure was utilized. Nineteen mathematical functions were employed as detailed in Table 2. The models included Brody, Gauss, Gompertz3P, Logistic3P, Lundqvist -Korf, Negative-exponential, Verhulst, Von-Bertalanffy, Weibull3P, Weighted Least Square, Blumberg, Bridges, Gompertz4P, Janochek, Logistic4P, Lopez4P, Morgan-Mercer-Flodin, Richards, and Weibull4P. The first 10 functions have three while the second nine functions have four parameters each. Gauss and Newton's algorithm was employed to achieve the convergence criteria.

Convergence was declared when the relative change in the sum of squared residuals between successive iterations was less than 1×10^{-5} (CONVERGE= 0.00001), with a maximum of 25,000 iterations allowed (MAXITER=25000) using the Newton-Raphson and Gauss algorithms. Models that failed to converge after 25,000 iterations were excluded from the final analysis.

Evaluations of the Goodness of Fit of the statistical models

To evaluate the goodness of fit of the 19 statistical models, multiple criteria including RMSE, AIC, AICc, BIC, and Adjusted R^2 (Adj-R2) were used. The models were compared within the four distinct genetic groups (M-H-1,2; and M-R-1,2) to identify the non-linear statistical models for the growth curve of each group. The SSE criterion, which represents the sum of squared errors, was derived from the SAS analysis tables. The other goodness of fit criteria was calculated using the non-linear statistical growth model with the following mathematical formula:

Eq1. $R^2 =$ Coefficient of determination $R^2 = \frac{SSM}{SST}$

Eq 2. R^2Adj = Adjusted coefficient of determination R^2-Adj = $1 - (\frac{n-1}{n-p}) \times (1- R^2 Models)$

Eq3. RMSE = Root Mean Square Error $RMSE = \sqrt[2]{\frac{SSE}{n-p}}$

Eq4. AIC = Akaike Information Criterion $AIC = n \times \ln(\frac{SSE}{n}) + 2\,p$

Eq5. AICc = Akaike Information Criterion correct $AICc = AIC + \frac{2p\times(p+1)}{n-p-1}$

Eq6. BIC = Bayesian Information Criterion $BIC = n \times \ln(\frac{SSE}{n}) + p \times \ln n$

Where n = number of observations; SSM = Sum of the square of models; SST = sum of the square of totals;

SSE = Sum of the square of errors; P = Number of parameters and ln = logarithm of nepers.

Mathematical Equations for Growth Curve Inflection Points

To characterize the growth dynamics of experimental groups, a three-parameter Gompertz growth model was fitted to body weight data. The general form of the Gompertz model is expressed as:

$$W_t = \alpha \times e\left(-e^{(-\beta \times (k\times t))}\right)$$

Where: W_t is the predicted body weight at time t (days), α represents the asymptotic maximum body weight (g), k is the maturation rate (per day), and t is the age at which the growth rate is maximized (the time at the inflection point.

Key growth parameters and inflection points were derived from the fitted model:

Asymptotic Body Weight (α\A): This parameter represents the theoretical maximum body weight.

Age at Inflection Point (AIP): This is the age at which the growth rate is maximal.

$$AIP = ln\ \beta / k$$

Weight at Inflection Point (WIP)**:** This is the body weight at the time of the inflection point.

$$WIP = \alpha \times e^{-1} \text{ or } (\alpha \times 0.368)$$

Table 1: Ingredients and chemical composition of the diet fed to Marandi chickens at the onset of lay (20 weeks of age; body weight: 1300-1450 g).

Part A		**Part B**	
Calculated composition	%	Ingredient	%
Dry Matter	88.00	Corn, grain	48.00
Metabolizable. Energy(kcal/g)	2.76	Soybean meal (42%CP)	19.33
Crude Protein	15.62	Wheat Bran	9.00
True Protein	14.66	Wheat Middling	5.70
Ether extract	4.65	Barley	12.00
Crude Fiber	3.28	Dicalcium phosphate	1.81
Calcium	0.95	Soy Oil	2.00
Total Phosphorus	0.82	Limestone	1.20
Available Phosphorus	0.52	Common Salt	0.35
Na	0.17	Vitamin Premix*	0.25
Cl	0.27	Mineral Premix*	0.25
Choline	1.57	DL-Methionine	0.08
Folate	0.98	L-Lysine HCL	0.03
Lys	0.82		
Met	0.30		
Thr	0.56		
Trp	0.23		

Vitamin Premix and Mineral Premix per kg of feed: vitamin A 11,000 IU; vitamin D3 3,500 IU; vitamin E 100 IU; vitamin K3 5 mg; vitamin B12 0.03 mg; riboflavin 12 mg; nicotinic acid 55 mg; pantothenic acid 15 mg; folic acid 2 mg; pyridoxine 6 mg; thiamine 3 mg; d-biotin 0.3 mg; choline 300 mg; Cu 10 mg; I 2 mg; Fe 50 mg; Mn 120 mg; Zn 100 mg; Se 0.3 mg (all mg per kg of feed).

Table 2: The used non-linear equations and their mathematical form for the growth curves of chickens

Non-linear equations	**Mathematical form**
Blumberg4P	$W_t = \alpha \times (k+t)^m / (W_h + (k+t)^m)$
Bridges4P	$W_t = W_h + \alpha \times \left(1 - \left(e^{(-k \times t)^m}\right)\right)$
Brody3P	$W_t = \alpha \times (1 - \beta \times e^{(-k \times t)})$
Gauss3P	$W_t = \alpha \times e^{\left(\left(\frac{1}{2} \times \left(\frac{t-b}{k}\right)^2\right)\right)}$
Gompertz3P	$W_t = \alpha \times e\left(-e^{\left(-\beta \times (k \times t)\right)}\right)$
Gompertz4P	$W_t = \alpha + (\beta - \alpha) \times e\left(\left(e^{(-c \times (t-m))}\right)\right)$
Janochek4P	$W_t = \alpha - ((\alpha - W_h) \times \left(e^{(-k \times t)^m}\right))$
Logistic3P	$W_t = \frac{\alpha}{\beta \times (1 + e^{(-k \times t)})}$
Logistic4P	$W_t = \alpha + \frac{(m - \alpha)}{(1 + e^{(-k \times (t-\beta))})}$
Lopez4P	$W_t = \frac{\alpha \times k^{((\beta+m) \times t^{\beta})}}{k^{(\beta + t \times \beta)}}$
Lundqvist-Korf 3P	$W_t = \alpha \times (e^{(-k \times t)^m})$
Morgan-Mercer-Flodin4P	$W_t = \frac{(\alpha \times \beta + k \times t^m)}{(\beta + t^m)}$
Negative exponential3P	$W_t = \alpha - (\beta \times e^{(-k \times t)})$
Richards4P	$W_t = \alpha / 1 - (\beta \times e(-k \times t)^{1/m})$
Verhulst3P	$W_t = \frac{\alpha}{(1 + \beta \times e^{(-k \times t)})}$
Von- Bertalanffy3P	$W_t = \alpha \times \left(1 - \beta \times (e^{-(k \times t)^3})\right)$
Weibull3P	$W_t = \alpha \times (1 - \frac{1}{3}) \times e^{-\beta (t-k)^3}$
Weibull4P	$W_t = \alpha - ((\alpha - \beta) \times \left(e^{(-k \times t)^m}\right))$
Weighted-Least-Square3P	$W_t = \alpha / 1 + (-\beta \times e^{(-k \times t)})$

Wt = body weight (gram) at t days of age; t = chicken's age in days; α = asymptotic weight (gram) or mature weight (gram); $\beta =$ scaling parameter (constant of integration); k = maturity index; m = shape parameter which allows a variable point of information; e = the Euler's number (~ 2.718282) Wh = chicken hatch weight (gram).

Results

The growth patterns of Marandi chickens across all genetic groups and both sexes are presented in Figure 1. As shown, both hens and roosters of the Marandi breed exhibited a relatively slow growth rhythm compared to commercial strains. This finding, along

with detailed descriptive statistics, is presented in Table 3. Furthermore, there is considerable dispersion (diversity) in their population, which may be attributed to a lack of racial purity.

Table 3: Summary of descriptive statistics of body weights in different age of Marandi chickens

Days	Sex	Flock	n	Mean	Min	Max	Std
1	H	2	61	29.67	21	39	4.00
1	R	2	54	29.85	23	42	4.12
2	H	1	120	33.15	25	42	3.28
2	R	1	70	32.90	27	44	3.06
7	H	2	60	44.31	30	65	6.47
7	R	2	52	44.44	32	58	6.12
9	H	1	118	45.37	30	69	8.23
9	R	1	69	46.62	31	70	8.59
14	H	2	59	61.47	36	99	12.60
14	R	2	51	61.89	35	88	11.44
16	H	1	117	73.09	44	108	15.97
16	R	1	68	75.22	46	125	15.90
28	H	2	58	132.14	55	211	32.38
28	R	2	50	135.51	59	214	31.90
30	H	1	117	169.89	99	317	43.83
30	R	1	68	181.08	102	277	42.48
49	H	2	58	363.57	123	586	85.93
49	R	2	50	381.70	90	577	103.40
58	H	1	116	423.38	245	607	82.31
58	R	1	68	501.98	254	715	105.78
72	H	1	116	712.02	466	980	118.48
72	R	1	68	897.10	371	1266	161.84
77	H	2	58	757.55	340	1110	125.59
77	R	2	49	880.17	472	1220	153.24
100	H	1	116	1070.98	655	1427	159.61
100	R	1	68	1436.98	422	1948	245.28
105	H	2	58	1072.85	714	1553	192.41
105	R	2	49	1362.81	958	1843	201.02
128	H	1	115	1292.47	787	1815	201.28
128	R	1	68	1780.4	1200	2130	231.05
133	H	2	58	1310.23	854	1927	179.32
133	R	2	48	1717.23	1263	2176	222.49
156	H	1	115	1504.06	813	2270	271.39
156	R	1	68	2114.5	1360	2485	311.27
161	H	2	58	1475.46	920	2166	220.51
161	R	2	48	2036.85	1560	2505	222.59
184	H	1	115	1677.94	1075	2445	279.01
184	R	1	68	2321.2	2165	2442	108.54
189	H	2	58	1614.62	1007	2190	243.96
189	R	2	48	1997.91	1616	2355	252.34

Sex: H= Hen, R=Rooster

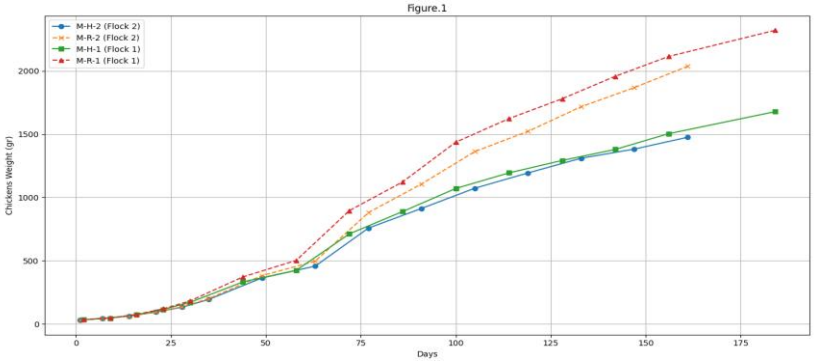


Figure 1. Raw growth curves of chickens across four genetic groups including Marandi hens' Flock 1,2 and Marandi roosters' Flock 1,2.

To thoroughly investigate their growth patterns, 19 nonlinear growth models (nine four-parameter and ten three-parameter functions) were fitted to the body weight data for both sexes of Marandi chickens. All models, except for the three-parameter negative exponential model for the M-R-1 group, converged successfully using the SAS NLIN procedure with a maximum of 25,000 iterations and a convergence criterion of 1×10^{-5}. The number of iterations for converged models ranged from 12 to 48, depending on the model complexity and genetic group. The goodness of fit of each model was assessed using AIC, AICc, BIC, RMSE, and Adj-R^2, with the lowest AIC serving as the primary selection criterion. The models evaluated included established functions such as Gompertz, Logistic, Richards, and Lopez, alongside more flexible models with enhanced mathematical capabilities, including Morgan-Mercer-Flodin 4P, Janoschek 4P, and Weibull 3P/4P. Statistical analysis using the GLM procedure in SAS software revealed significant differences between Marandi hens and roosters, even when reared in two separate flocks.

Table 4: Evaluation criteria for three- and four-parameter functions fitted to the growth curve of chickens of 2 genetic group M-H-1,2

Genetic group	Function[€]	RMSE	AIC	AICc	BIC	ΔAIC	Adj-R2
M-H-1	**Morgan-Mercer-Flodin4P[1*]**	**144.78**	**18894.17**	**18894.19**	**18916.36**	**0.02**	**0.976**
	Blumberg4P	144.92	18897.96	18897.98	18920.16	0.02	0.976
	Gompertz3P[2*]	**145.03**	**18898.86**	**18898.87**	**18915.50**	**0.01**	**0.976**
	Gompertz4P	145.00	18900.14	18900.17	18922.34	0.03	0.976
	Richards4P	145.03	18900.82	18900.84	18923.01	0.02	0.976
	Bridges4P	145.44	18901.66	18901.68	18923.85	0.02	0.942
	Janochek4P	145.40	18910.62	18910.64	18932.82	0.02	0.976
	Weibull4P	146.03	18926.79	18926.81	18948.98	0.02	0.976
	Logistic4P	146.29	18933.53	18933.55	18955.73	0.02	0.976
	Verhulst3P	149.75	19020.19	19020.21	19036.84	0.02	0.975
	Lopez4P	159.45	19260.54	19260.56	19282.74	0.02	0.971
	Negative exponential3P	163.26	19337.96	19337.98	19354.61	0.02	0.927
	Brody3P	163.22	19347.15	19347.17	19363.80	0.02	0.970
	Weibull3p	163.22	19347.15	19347.16	19363.80	0.01	0.969
	Von Bertalanffy3P	178.67	19690.47	19690.49	19707.12	0.02	0.964
	Logistic3P	274.66	21322.67	21322.69	21339.32	0.02	0.914
	Gauss3P	274.66	21322.68	21322.70	21339.33	0.02	0.915
	Lund qvist-Korf3P	274.66	21322.69	21322.71	21339.34	0.02	0.914
	Weighted Least Square3P	456.21	23248.75	23248.76	23265.39	0.01	0.765
M-H-2	**Morgan-Mercer-Flodin4P[1*]**	**163.29**	**8880.39**	**8880.44**	**8899.47**	**0.05**	**0.973**
	Blumberg4P	163.43	8881.86	8881.91	8900.94	0.05	0.973
	Gompertz3P[2*]	**163.62**	**8882.94**	**8882.97**	**8897.25**	**0.03**	**0.973**
	Richards4P	163.16	8883.1	8883.15	8902.18	0.05	0.973
	Gompertz4P	163.3	8884.6	8884.65	8903.68	0.05	0.973
	Janochek4P	163.9	8886.89	8886.91	8905.97	0.02	0.930
	Bridges4P	163.9	8886.89	8886.91	8905.97	0.02	0.930
	Logistic4P	164.62	8888.51	8888.56	8907.59	0.05	0.930
	Weibull4P	164.07	8888.74	8888.79	8890.78	0.05	0.967
	Verhulst3P	169.15	8943.93	8943.96	8958.24	0.03	0.971
	Lopez4P	173.00	8985.14	8985.19	9004.22	0.05	0.970
	Negative exponential3P	176.75	9010.11	9010.14	9024.42	0.03	0.919
	Brody3P	176.65	9019.46	9019.48	9033.77	0.02	0.969
	Weibull3p	176.67	9019.47	9019.49	9033.78	0.02	0.968
	Von Bertalanffy3P	200.63	9241.18	9241.21	9255.49	0.03	0.959
	Logistic3P	280.89	9827.37	9827.40	9841.68	0.03	0.921
	Gauss3P	280.89	9827.38	9827.41	9841.69	0.03	0.920
	Lund qvist-Korf3P	280.89	9827.39	9827.42	9841.70	0.03	0.920
	Weighted Least Square3P	466.09	10709.53	10709.55	10723.83	0.02	0.781

[£] M-R-1 = Marandi Hen-Flock 1 and M-R-2 = Marandi Hen-Flock 2.
[€] The function with the best fit within each genetic group was shown in bold.
[*]1 and 2 Ranking of the best fitted model according to the number of model parameters. ΔAIC = AICc - AIC

The results of model fitting, summarized in Tables 4 and 5, showed that the best-fitting models varied across genetic groups. Results indicated that the Morgan-Mercer-Flodin (4P) model ranked among the best-fitting functions for both Marandi hen flocks (M-H-1 and M-H-2), while the Bridges (4P) model ranked among the best-fitting models for both rooster flocks (M-R-1 and M-R-2). Among the ten three-parameter models, the Gompertz (3P) model consistently proved to be among the most appropriate for both sexes across all genetic groups. However, four-parameter models generally showed superior fit in terms of AIC and RMSE compared to three-parameter alternatives. It is important to note that the differences between the top 4-5 models for each group were small, suggesting that multiple models could be considered equally suitable for describing the growth curve of Marandi chickens.

A comparison of the observed average weight of both flocks with the fitted values from the Gompertz (3P) model (which was among the best three-parameter models across all genetic groups) showed a remarkable consistency, as depicted in Figure 2.

Table 5: Evaluation criteria for three- and four-parameter functions fitted to the growth curve of chickens of 2 genetic group M-R-1,2

Genetic group[£]	Function[€]	RMSE	AIC	AICc	BIC	ΔAIC	Adj-R^2
M-R-1	**Bridges4P[1*]**	**136.55**	**8936.94**	**8936.98**	**8956.18**	**0.04**	**0.957**
	Richards4P	136.33	8943.77	8943.81	8963.02	0.04	0.978
	Blumberg4P	136.36	8944.16	8944.21	8963.41	0.05	0.978
	Janochek4P	136.48	8945.77	8945.82	8965.02	0.05	0.978
	Gompertz4P	136.61	8947.55	8947.59	8966.80	0.04	0.978
	Logistic4P	136.97	8952.32	8952.36	8971.57	0.04	0.978
	Morgan-Mercer-Flodin4P	137.08	8953.72	8953.77	8972.97	0.05	0.978
	Gompertz3P[2*]	**137.49**	**8957.21**	**8957.24**	**8971.65**	**0.03**	**0.978**
	Verhulst3P	138.96	8976.47	8976.50	8990.91	0.03	0.977
	Weibull4P	141.27	8998.59	8998.63	9017.84	0.04	0.954
	Lopez4P	163.84	9277.97	9278.01	9297.22	0.04	0.969
	Von Bertalanffy3P	170.65	9349.89	9349.91	9364.32	0.02	0.966
	Negative exponential3P	177.02	9406.20	9406.23	9420.64	0.03	0.928
	Weibull3p	176.92	9415.56	9415.58	9429.99	0.02	0.963
	Brody3P	176.93	9415.63	9415.65	9430.06	0.02	0.963
	Logistic3P	311.98	10446.70	10446.72	10461.13	0.02	0.887
	Gauss3P	311.98	10446.70	10446.72	10461.13	0.02	0.887
	Lund qvist-Korf3P	311.98	10446.69	10446.72	10461.13	0.03	0.886
	Weighted Least Square3P	530.26	11410.99	11411.01	11425.42	0.02	0.672
M-R-2	**Bridges4P[1*]**	**157.94**	**5617.00**	**5617.08**	**5634.27**	**0.08**	**0.949**
	Morgan-Mercer-Flodin4P	158.26	5619.28	5619.35	5636.55	0.07	0.949
	Logistic4P	158.48	5620.82	5620.89	5638.09	0.07	0.949
	Blumberg4P	157.55	5624.42	5624.50	5641.70	0.08	0.976
	Richards4P	157.56	5624.44	5624.51	5641.72	0.07	0.976
	Gompertz4P	157.69	5625.36	5625.44	5642.64	0.08	0.976
	Gompertz3P[2*]	**158.07**	**5626.06**	**5626.10**	**5639.02**	**0.04**	**0.975**
	Janochek4P	157.80	5626.13	5626.20	5643.40	0.07	0.976
	Verhulst3P	161.07	5646.92	5646.97	5659.88	0.05	0.975
	Weibull4P	161.67	5653.03	5653.10	5670.31	0.07	0.971
	Lopez4P	180.98	5778.29	5778.36	5795.56	0.07	0.970
	Negative exponential3P	193.90	5842.25	5842.29	5855.20	0.04	0.920
	Brody3P	193.72	5851.78	5851.82	5864.74	0.04	0.970
	Weibull3p	193.72	5851.78	5851.82	5864.74	0.04	0.968
	Von Bertalanffy3P	194.21	5854.59	5854.64	5867.55	0.05	0.959
	Logistic3P	333.60	6455.04	6455.08	6467.99	0.04	0.921
	Gauss3P	333.60	6455.03	6455.07	6467.99	0.04	0.921
	Lund qvist-Korf3P	333.60	6455.03	6455.07	6467.10	0.04	0.921
	Weighted Least Square3P	559.66	7029.35	7029.39	7042.30	0.04	0.781

[£] M-R-1 = Marandi Rooster-Flock 1 and M-R-2 = Marandi Rooster-Flock 2.
[€] The function with the best fit within each genetic group was shown in bold.
[*]1 and 2 Ranking of the best fitted model according to the number of model parameters. Δ AIC =AICc - AIC

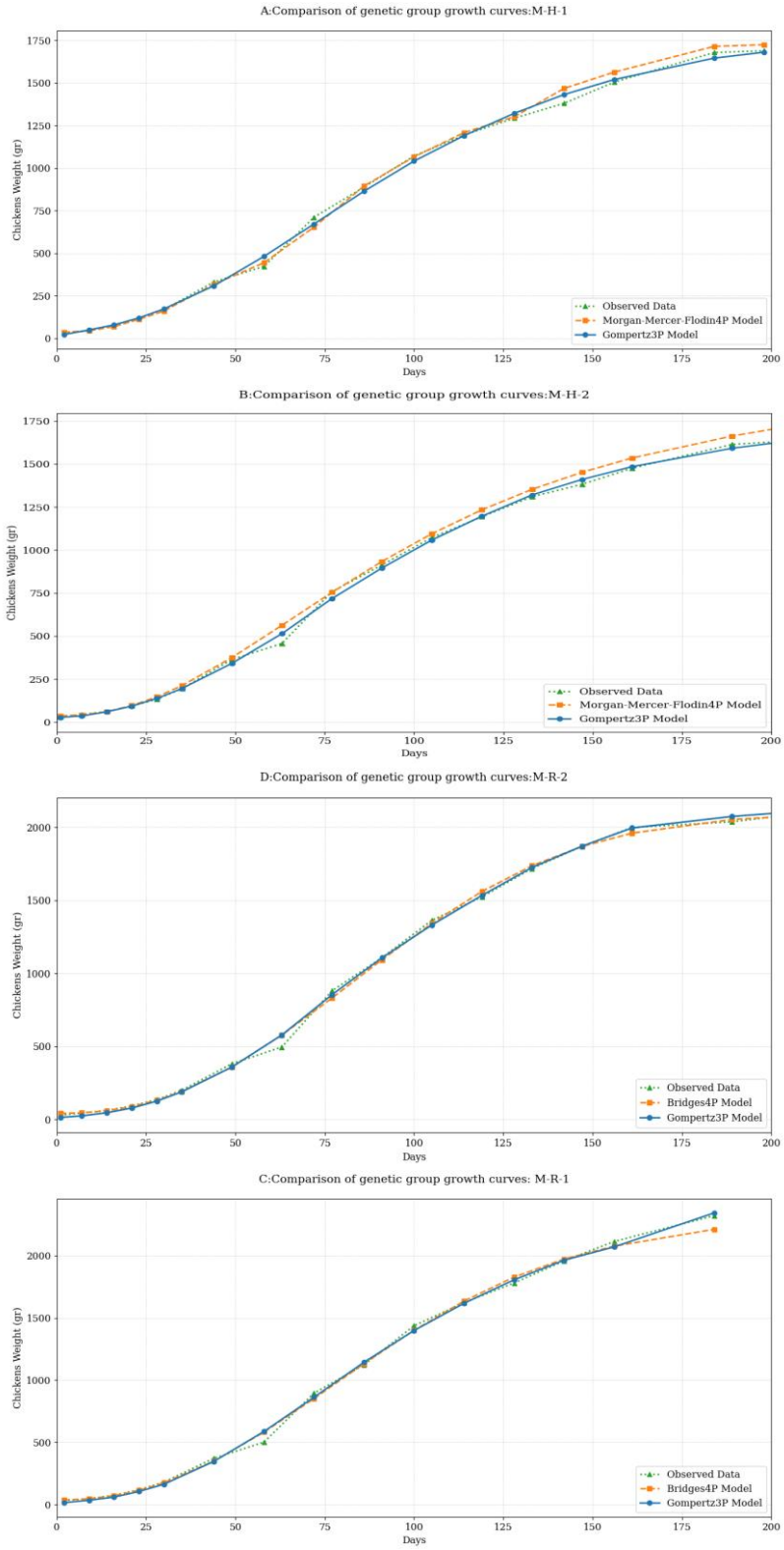


Figure 2. Comparison of nonlinear growth curves in 4 genetic groups of Merandi chickens: the best Bridges4P model vs. Gompertz3p model vs. observed weights in M-R-1 (C) and M-R-2 (D), and the best Morgan-Mercer-Flodin4p model vs. Gompertz3p model vs. observed weights in M-H-1 (A) and M-H-2 (B).

Upon examining the nonlinear growth curve graph with the observed chick weight data, it is evident that up to 28 days of age, the chicks maintained an approximately equal average weight. Divergences

among the four genetic groups began to appear from this point onward. The highest and lowest growth rates were observed in groups M-R-1 and M-H-2, respectively. The detailed description of each nonlinear growth curve parameter, categorized into three- and four-parameter models for the experimental groups, is presented in Tables 6 and 7. These tables illustrate the predicted parameters of the nonlinear growth curves for each genetic group. Each estimated growth parameter (A, B, K, and m) corresponds to the asymptotic (mature) weight (in grams), the shape parameter, the maturity index, and the scaling parameter, respectively. The unique shape of the growth curve, along with its parameters and the weight and age at the inflection point (WIP, AIP), can serve as a distinctive breed identifier.

Table 6: Estimated growth curve parameters from the 3-parameters function for Marandi chickens

Function£	Genetic group	Parameters€		
		A	B	K
Brody3P	M-H-1	3693.6 ± 197.4	1.03 ± 0.00356	0.00328 ±0.000229
	M-H-2	3995.6 ± 358.6	1.02 ± 0.00544	0.00312 ± 0.000361
	M-R-2	236892 ± 1180794	1.00 ± 0.00323	0.000062 ±0.000308
Gompertz3p	M-H-1	1728.8 ± 15.68	1.51 ± 0.0242	0.0212 ± 0.000431
	M-H-2	1810.5 ± 27.86	1.46 ± 0.0370	0.0205 ± 0.000682
	M-R-1	2293.6 ± 36.34	1.68 ± 0.0300	0.0219 ± 0.000564
	M-R-2	2427.3 ± 54.14	1.65 ± 0.0405	0.0225 ± 0.000810
Gauss	M-H-1	2584.4 ± 7.61	38.90 ±12873.7	0.00475± 0.000060
	M-H-2	2017.46 ± 7.88	39.72 ± 226.8	-0.00476± 0.000089
	M-R-1	797.8 ±7.29	39.70 ± 5.3848	0.00602 ±0.000098
	M-R-2	1143.4 ±7.91	40.47 ± 5705.5	-0.00615 ± 0.000130
Logistic 3p	M-H-1	58834.6 ± 11461.1	288.43 ± 5.65	0.00949 ±0.000119
	M-H-2	11938.5 ± 43821.0	305.44 ± 8.75	0.00952 ± 0.000178
	M-R-1	17215.5 ± 50661.0	282.53 ± 7.85	0.0120 ± 0.000196
	M-R-2	34945.5 ± 10711.1	312.36 ±10.93	0.0123 ± 0.000259
Lundqvist-Korf 3P	M-H-1	288.4 ± 5.65	-0.06 ± 9.5256	0.1526 ±23.3719
	M-H-2	305.4 ± 8.75	--0.06 ± 22.9997	0.1518 ± 55.6517
	M-R-1	282.5± 7.85	-0.08 ± 0.3963	0.1431± 0.6738
	M-R-2	312.3 ± 10.94	-0.08 ± 20.3760	0.1480± 36.2816
Negative exponential3P	M-H-1	3693.5 ± 212.8	3811.22 ± 207.6	0.00328 ± 0.000247
	M-H-2	3995.6 ± 382.7	4110.24 ± 374.0	0.00312 ± 0.000386
	M-R-2	237396 ± 1871952	237548 ± 1871941	0.000061 ± 0.000486
Verhulst3P	M-H-1	1592.2 ± 10.73	24.14 ± 1.08	0.0372 ± 0.000656
	M-H-2	1659.6 ± 18.80	21.45 ± 1.46	0.0358 ± 0.00103
	M-R-1	2015.3 ± 22.75	37.18 ± 2.02	0.0415 ± 0.000833
	M-R-2	2123.3 ± 33.68	34.53 ± 2.58	0.0426 ± 0.00122
Von Bertalanffy3P	M-H-1	1457.1 ± 8.70	2.26 ± 0.0361	0.0126 ± 0.000122
	M-H-2	1502.1 ± 14.50	2.18 ± 0.0562	0.0126 ± 0.000204
	M-R-1	1768.4 ± 17.90	2.48 ± 0.0441	0.0131 ± 0.000139
	M-R-2	1858.5 ± 24.92	2.42 ± 0.0593	0.0137 ± 0.000195
Weibull3P	M-H-1	3693.6 ± 197.4	344.2 ± 23.06	0.00109 ± 0.000076
	M-H-2	3995.6 ± 358.6	360.7 ± 40.20	0.00104 ± 0.000120
	M-R-1	44654.1 ±43054.6	3530.2 ± 3457.4	0.000104±0.000102
	M-R-2	231136 ± 76220.1	17433.1± 5764.7	0.000021 ± 0.00006
Weighted-Least-Square3P	M-H-1	1065.1±16.29	-6.84 ± 1027.0	0.00254 ± 0.3934
	M-H-2	1131.3 ± 24.85	-6.68± 851.6	0.00258 ± 0.3286
	M-R-1	1015.4 ± 27.6913	-7.27 ± 2702.2	0.00281 ± 1.0428
	M-R-2	1114.8 ± 37.59	-7.60 ± 2115.6	0.00285± 0.8164

£ M-H -1= Marandi Hen Flock1; M-R-1= Marandi Rooster Flock 1; £ M-H -2= Marandi Hen Flock 2 and M-R-2= Marandi Rooster Flock 2.
€ A = asymptotic weight (g) or mature weight (g); B=scaling parameter (constant of integration); K = maturity index.

The inflection point parameters were estimated using the Gompertz (3P) model. The WIP for M-H-1, M-H-2, M-R-1, and M-R-2 was estimated to be 656.12 g, 683.97 g, 988.49 g, and 904.00 g, respectively. Similarly, the AIP for M-H-1, M-H-2, M-R-1, and M-R-2 was estimated to be 70.13 days, 71.13 days, 72.00 days, and 72.27 days, respectively.

The predicted parameters of nonlinear growth curves illustrate the dynamics of growth patterns in native Marandi chickens. Each estimated growth parameter (A, B, K, and m) represents the asymptotic (mature)

body weight (in grams), the shape parameter, the maturation index, and the scaling factor governing the growth trajectory, respectively.

Residual diagnostic plots (residuals vs. fitted values and residuals vs. age) for the selected models – four-parameter MMF (for M-H-1 and M-H-2), four-parameter Bridges (for M-R-1 and M-R-2), and three-parameter Gompertz (for all four genetic groups) – are provided as Supplementary Figure S1. These plots confirmed the random distribution of residuals and the absence of systematic deviations, supporting the adequacy of the selected models.

Table 7: Estimated growth curve parameters from the 4-parameters function for Marandi its chickens

Function£	Genetic group	Parameters€			
		A	B	K	m
Bridges4P	M-H-1	1642.5 ± 21.25	25.61 ± 7.6330	0.000114 ± 0.000023	1.94 ±0.0459
	M-H-2	1756.0 ± 44.04	18.96 ± 13.8179	0.000194 ± 0.000061	1.82 ± 0.0731
	M-R-1	2048.2 ± 35.03	41.66 ±8.4950	0.000018 ± 0.000005	2.34 ± 0.0597
	M-R-2	2199.4 ± 57.20	37.18 ± 13.3902	0.000031± 0.000011	2.24 ± 0.0814
Blumberg4P	M-H-1	1816.6 ± 37.74	9628948±18146885	30.09 ± 8.7543	3.34 ± 0.3504
	M-H-2	1989.9 ± 84.37	420877 ± 892936	18.21 ± 10.3771	2.73 ± 0.4128
	M-R-1	2204.5 ± 53.29	21570000±14360000	82.06 ± 26.4431	5.96 ± 1.1235
	M-R-2	2389.7 ± 90.63	27490000±16950000	55.81 ± 24.7593	4.83 ± 1.0872
Gompertz4p	M-H-1	1721.0 ± 17.74	10.01 ± 11.5615	0.0216 ± 0.000632	71.85 ± 0.8342
	M-H-2	1821.1 ± 34.35	-13.49 ±24.0120	0.0201±0.001030	70.92 ± 1.4885
	M-R-1	2232.2 ± 36.65	39.84 ± 10.7514	0.0238 ± 0.000791	77.30 ± 0.9082
	M-R-2	2380.1 ± 57.16	30.87 ± 17.7625	0.0238 ± 0.001150	73.79 ± 1.2654
Janochek4P	M-H-1	1668.1 ± 17.52	25.61 ± 7.6330	0.000114 ± 0.000023	1.94 ± 0.0459
	M-H-2	1774.9 ± 37.02	18.96 ± 13.8179	0.000194 ± 0.000061	1.82 ± 0.0731
	M-R-1	2089.9 ± 31.89	41.66 ± 8.4950	0.000018 ± 0.000004	2.35 ± 0.0597
	M-R-2	2236.6 ± 51.97	37.18 ± 13.3902	0.000031 ± 0.000011	2.24 ± 0.0814
Logistic4p	M-H-1	1660.6 ± 15.03	-164.1± 23.3106	-0.0290 ±0.000976	81.01 ± 1.0522
	M-H-2	1758.1 ± 29.68	-234 ± 49.5421	-0.0263 ± 0.00156	79.25 ± 1.9818
	M-R-1	2084.6 ± 28.45	-82.97± 18.6966	-0.0361 ± 0.00126	86.52 ± 0.9041
	M-R-2	2218.2 ± 44.32	-114.4 ±31.1576	-0.0358 ± 0.00180	82.41 ± 1.2622
Lopez4P	M-H-1	445.0 ± 1031.1	1.41 ± 0.3860	36.35 ± 67.3372	-56.07 ± 67.3372
	M-H-2	435.1 ± 1437.5	1.42 ± 0.5531	34.54 ± 90.6689	-54.55 ± 22.4822
	M-R-1	235.6 ± 850.3	1.62 ± 0.5913	24.77 ± 58.6154	-47.34 ± 18.9396
	M-R-2	273.7 ± 1182.2	1.61 ± 0.7138	24.73 ± 71.1569	-55.14 ± 25.1650
Morgan-Mercer-Flodin4P	M-H-1	1902.8 ± 33.05	64908.3±19630.9	2.42 ± 0.0727	42.25 ± 7.2876
	M-H-2	2067.7 ± 69.46	28738.8±13259.5	2.22 ± 0.1129	36.08 ± 13.2797
	M-R-1	2406.1 ± 56.99	464997±180543	2.84 ± 0.0940	55.94 ± 8.2878
	M-R-2	2600.5 ± 92.93	228398±117974	2.70 ± 0.1275	53.48 ± 13.0370
Richards4P	M-H-1	1732.2 ± 23.83	17.41± 4.6570	0.0210 ± 0.00122	-0.0140 ± 0.0738
	M-H-2	1859.0 ± 50.59	13.83 ± 8.2309	0.0181 ± 0.00185	-0.15 ± 0.1152
	M-R-1	2157.2 ± 41.41	27.06 ± 5.1248	0.0285 ± 0.00200	0.34 ± 0.0972
	M-R-2	2319.8 ± 68.11	25.65 ± 7.9288	0.0270 ± 0.00272	0.23 ± 0.1302
Weibull4P	M-H-1	2474.9 ± 96.94	64.47 ± 7.0295	-1.1657 ± 0.0585	55.73 ± 1.0300
	M-H-2	2829.4 ± 223.1	62.08 ± 12.6449	-1.0325 ± 0.0915	53.94 ± 1.7846
	M-R-1	3257.3 ± 178.5	77.93 ± 8.3326	-1.3109 ± 0.0810	64.31 ± 0.9489
	M-R-2	3611.9 ± 300.3	78.88 ± 12.8568	-1.2273 ± 0.1081	60.84 ± 1.2965

£ M-H -1= Marandi Hen Flock1; M-R-1= Marandi Rooster Flock 1; £ M-H -2= Marandi Hen Flock 2 and M-R-2= Marandi Rooster Flock 2.

€ A = asymptotic weight (g) or mature weight (g); B=scaling parameter (constant of integration); K = maturity index and m = shape parameter which allows a variable point of information.

Comparison of Best 3P vs. Best 4P Models

To determine whether the improvement from three-parameter to four-parameter models justifies the additional parameter, ΔAICc values were compared between the best 3P model (Gompertz 3P) and the best 4P model for each respective group (MMF for

M-H-1 and M-H-2; Bridges for M-R-1 and M-R-2) within each subgroup (ΔAICc = AICc of the 4P model – AICc of the 3P model; negative values indicate superior fit of the 4P model). For M-H-1, M-H-2, M-R-1, and M-R-2, the ΔAICc values were −4.68, −5.23, −20.26, and −9.02, respectively, all exceeding the conventional threshold of 2 (Burnham & Anderson, 2002). Evidence ratios indicated that the best 4P model was 10 to 25,000 times more likely to be the true best model than Gompertz 3P. Therefore, the additional parameter in four-parameter models is fully justified by the substantial improvement in fit, particularly for dual-purpose Marandi chickens where growth trajectories exhibit asymmetry and delayed inflection points not adequately captured by simpler three-parameter functions.

Discussion

Conservation of indigenous poultry populations can significantly contribute to increasing biodiversity in the poultry industry. Research has shown that nonlinear models are considered the best for modeling the growth of indigenous poultry (González Ariza *et al*., 2021). This study, focusing on the growth patterns of Marandi chickens, is unique in that it examined 19 nonlinear growth curve models with three- and four-parameters. The models and their ability to capture variability and performance, both observationally and predictively, are influenced by the specific characteristics of the indigenous population data.

Fitted growth curve models convert raw observed data over time in animals and poultry into interpretable parameters, such as asymptotic weight (A) and growth rate coefficient (K) at maturity (González Ariza *et al*., 2021). Given the heritability of growth curve parameters, particularly A and K in poultry and animals, breeding plans and strategies can be formulated for indigenous chickens through genetic selection or dietary interventions. This enables the improvement of the growth curve shape in indigenous poultry according to breed objectives (Setiaji *et al*., 2025). In commercial chickens, due to their higher genetic potential developed by geneticists and breeders, they exhibit the highest growth rates and possess uniform growth curve parameters, leading to reduced intra-breed variation. Conversely, Marandi indigenous chickens show significant breed variation, as no specific breeding programs have been implemented on them, suggesting a high potential for altering growth curve parameters.

Although mixed models or ANOVA on parameter estimates could be used for formal statistical comparisons between genetic groups, such analyses were not performed in the present study. This decision was due to the small sample sizes within some subgroups and the primary focus of this study on evaluating and comparing the goodness of fit of nonlinear growth models rather than testing hypotheses between groups. Nevertheless, the numerical differences in parameter estimates across genetic groups (as shown in Table 6) provide valuable insights into the growth potential of Marandi chickens. Future studies with larger sample sizes are encouraged to apply mixed models for robust statistical comparisons of growth parameters across genetic groups and sexes.

Selection of Appropriate Growth Models Across Four Genetic Groups

In the present study, four genetic groups were investigated: M-H-1, M-H-2, M-R-1, and M-R-2. The selection of the most appropriate growth model varied across these groups. The Morgan-Mercer-Flodin (MMF) 4P model was identified as the best-fitting model for both hen flocks (M-H-1 and M-H-2). In contrast, the Bridges 4P model exhibited superior performance for both rooster flocks (M-R-1 and M-R-2). This indicates that the choice of the most suitable growth model is influenced not only by sex but also by the specific genetic background of each flock. The MMF model showed a more accurate model fit for male and female partridges, which aligns with the findings for Marandi hens in the present study (Ghavi Hossein-Zadeh *et al*., 2025). In contrast, for Korean native KNC chickens, the Logistic model was introduced as the best growth pattern (Manjula *et al*., 2017). However, in the M-R-1 and M-R-2 genetic groups (both Marandi roosters), the Bridges 4P model was the best among all fitted models, consistent with the research by Bo *et al*. (2022) on indigenous Ri roosters in Vietnam. For indigenous hybrid roosters, the Logistic 4P function was identified as the most suitable model. This conclusion is supported by the research of Narinc *et al*. (2010) and Kumar *et al*. (2022), who similarly found the Logistic model to be an accurate descriptor of growth in various chicken

breeds. Yang *et al*. (2006) further confirmed the higher accuracy of the Logistic function for describing the growth pattern in Jinga yellow chickens. Pourhamidi *et al*. (2024) reported an average actual weight of 1060 grams at 126 days of age. In contrast, the chickens from flocks 1 and 2 reached body weights of 1070.98 and 1072.85 grams at 100 and 105 days of age, respectively. This difference indicates that chickens in this study reached the target weight 21 to 26 days earlier. According to descriptive statistics (Table 3), Marandi chickens in flocks 1 and 2 had an average body weight (BW) of 1278.42 and 1251.97 grams at 126 days of age, respectively. This weight and time difference might be due to climate, nutrition, management, population size, and breed purity.

Performance of the Gompertz 3P Model

In most studies conducted on commercial and indigenous chickens, the Gompertz 3P model has been introduced as the most suitable, providing a good representation of the actual nonlinear curve (Ndri *et al*., 2018; Brito *et al*., 2021; Loengbudnark *et al*., 2025). Also, considering Figures 2 and the results obtained from model fitting, the Gompertz 3P model ranked among the best three-parameter models for all tested individuals and both sexes. Wu *et al*. (2024) on indigenous yellow chickens, Zhou *et al*. (2025) on Wenshang breed chickens in China, and Ghaderi-Zefrehei *et al*. (2024) on Isfahani indigenous chickens reported Gompertz 3P as the best nonlinear growth pattern for these chickens.

Comparison of Growth Parameters with Other Breeds

In the study by Zárate-Contreras *et al*. (2022) on Mexican Creole chickens and roosters, K values were reported as 0.0220 and 0.0237, respectively. Furthermore, Aggrey (2003) noted that in Athens Canadian breed chickens, the K value for roosters was 0.0224 and for hens was 0.0216. Based on the results, the maturity coefficient (K) in flocks 1 and 2 of Marandi hens (0.0205 and 0.0212) and roosters (0.0219 and 0.0225) were consistent with these previous findings. For the growth rate at maturity (K), Ait Kaki and Moula (2013) estimated values of 0.0260 and 0.0294 g/day on Kabyle chickens, while Yapi Gnaoré *et al*. (2011) reported values of 0.0189 to 0.0205 g/day on indigenous local chickens in the Ivory Coast. González Ariza *et al*. (2021) stated that in Spanish Utrera chickens, based on goodness of fit criteria, the Von Bertalanffy model provided the best description of the nonlinear growth curve. For the growth parameter A, the estimated asymptotic weight for black variety roosters and hens was 2605.96 g and 2032.61 g, respectively, while for the white variety the estimated asymptotic weight (A) was 2442.99 g for roosters and 1874.24 g for hens. In terms of parameter A, Marandi hens and roosters in flock 2 were consistent with these ranges, but the model fit differed. Bo *et al*. (2022) reported that asymptotic weights in Ri breed hens and roosters were estimated at 1670 g and 2380 g, respectively. For Chinese WB chickens, the Gompertz 3P model has been confirmed as the most suitable among three-parameter models, with curve parameters 'A' equal to 1574.5 g, 'k' equal to 0.15, and WIP and AIP being 579.22 g and 58.59 days, respectively. This aligns with the WIP of Marandi hens in flock 1 (656.12 g). For Isfahani indigenous chickens, the Gompertz 3P growth curve parameters for 'A' and 'k' were reported as 2149.4 g and 0.0240, respectively (González Ariza *et al*., 2021). The 'k' parameter was consistent with M-R-2. Mata-Estrada et al. (2020) reported that the growth rate parameters for commercial broiler strains were substantially higher than those observed in indigenous breeds, with values ranging from 0.0915 to 0.0985 g/day for females and males, respectively. This suggests that Marandi hens and roosters have a slower growth rate compared to commercial chickens, representing a distinct range for an indigenous laying breed.

Inflection Point Parameters

The inflection point parameters for the Gompertz 3P model were compared between hens and roosters. For M-H-1, the weight at inflection point (WIP) was 656.12 g for hens and 988.49 g for roosters. For M-H-2, WIP was 683.97 g for hens and 904.10 g for roosters. In both flocks, roosters reached a higher WIP than hens. The average age at inflection point (AIP) was approximately 71 days for all birds. These findings are consistent with previous reports in other chicken populations, where males also exhibited higher weight at the inflection point than females (Rizzi *et al*., 2013; Eleroğlu *et al*., 2014).

Comparison with External Studies on Four-Parameter Models

The superior fit of four-parameter models (MMF for hen flocks and Bridges for rooster flocks) over three-parameter alternatives in Marandi chickens is

consistent with previous reports in other indigenous breeds. Plaengkaw *et al*. (2026) demonstrated that the Hossfeld model, a four-parameter function, provided the best fit for growth patterns in KU Phuphan and Pradu Hang Dam indigenous chickens, with roosters exhibiting higher asymptotic weights and growth rates than hens. Similarly, studies on Black Utrerana chickens have confirmed that sexual dimorphism is primarily reflected in asymptotic weight, with roosters reaching significantly higher mature weights than hens. The excellent performance of the Gompertz 3P model across all genetic groups in the present study aligns with findings in Noiler and broiler strains, where the Gompertz model best described growth trajectories with the lowest AIC and RMSE values. Furthermore, Siegel and Honaker (2025) demonstrated that sexual dimorphism in chicken growth is remarkably stable across generations, with the difference between roosters and hens increasing from approximately 8% at 4 weeks to over 18% at 8 weeks of age, supporting our observation of divergence from 10 weeks onward.

Justification of Four-Parameter Models

The superiority of four-parameter models over three-parameter alternatives was statistically confirmed through ΔAICc comparisons, as detailed in Section 3.1. In summary, the ΔAICc values for M-H-1 (−4.68), M-H-2 (−5.23), M-R-1 (−20.26), and M-R-2 (−9.02) all exceeded the conventional threshold of 2 (Burnham & Anderson, 2002), with evidence ratios indicating that the best 4P model was 10 to 25,000 times more likely to be the true best model than Gompertz 3P.

These findings confirm that the additional parameter in four-parameter models is fully justified, particularly for dual-purpose Marandi chickens, whose growth trajectories exhibit asymmetry and delayed inflection points not adequately captured by simpler three-parameter functions. The improved fit of the MMF model for hens and the Bridges model for roosters underscores the importance of model flexibility in accurately describing growth patterns in indigenous breeds with significant sexual dimorphism and genetic variability.

Therefore, for future growth studies on this breed, the MMF 4P model for hens and the Bridges 4P model for roosters should be prioritized, as these provided the most accurate descriptions of growth trajectories based on all evaluated criteria.

Limitations of the Study

The present study has several limitations, including the relatively small sample sizes in some subgroups (e.g., M-H-2, n=61; M-R-2, n=54) due to the limited availability of purebred Marandi chickens and the high cost of maintaining two separate flocks over the growth period. Larger sample sizes would have improved the precision of parameter estimates, particularly for the four-parameter models, and allowed for more robust statistical comparisons between flocks and sexes. Despite these limitations, the comprehensive comparison of 19 nonlinear models provides valuable insights into the growth characteristics of this indigenous dual-purpose breed.

Conclusion

Based on the evaluation of 19 nonlinear growth models using AICc, BIC, RMSE, and Adj R^2, the Morgan-Mercer-Flodin (4P) model was identified as the most appropriate function for describing growth in Marandi hen flocks, while the Bridges (4P) model was the most suitable for Marandi rooster flocks. Four-parameter models consistently outperformed three-parameter alternatives across all genetic groups, as confirmed by lower AICc and RMSE values. Significant sexual dimorphism was observed, with roosters reaching higher asymptotic weights and later inflection points compared to hens. Based on these findings, the following evidence-based recommendations are proposed. For research applications, the MMF 4P model for hens and the Bridges 4P model for roosters should be prioritized in future growth studies on this breed, as these provided the most accurate descriptions of growth trajectories. For management practices, separate feeding strategies for males and females from 10 weeks of age are recommended to optimize growth performance, given the divergence in growth trajectories observed after this age. For breeding programs, the identified growth curve parameters (asymptotic weight, maturity rate, and inflection point) can serve as selection criteria to improve growth efficiency, noting that this study was limited to phenotypic characterization and genetic validation would require further investigation.

Overall, the identified models offer reliable frameworks for growth description and support evidence-based management decisions for Marandi chickens based on the phenotypic data analyzed in this study.

Declarations

Ethics approval and consent to participate:

This study was reviewed and approved by the Animal Ethics Committee of Tabriz University (Approval number: 1404.133). All animal procedures were performed in accordance with the National Guideline for the Care and Use of Laboratory Animals in Iran and the ARRIVE guidelines.

Consent for publication:

All authors have consented to the publication of this article and related data.

Data availability

The data utilized and/or examined in this research can be obtained from the corresponding author if a valid request is made.

Competing interest

The authors declare that they have no competing interests that could influence the reported results in the present paper.

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Author Contributions

MTZ: Data curation; Formal analysis; Methodology; Writing - review & editing; Writing - original draft; investigation; Software; Project administration; Resources.

KH: Project administration; Validation; Supervision; Methodology; Conceptualization; Writing - review & editing.

SA: Software; Formal analysis; Methodology; Validation; Project administration; Conceptualization.

A J: Validation; Supervision; Visualization.

MO: Validation; Supervision; Investigation.

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Refrences

Abbas AA, Yosif AA, Shukur AM & Ali FH. 2014. Effect of genotypes, storage periods and feed additives in broiler breeder diets on embryonic and hatching indicators and chicks blood parameters. Scientia Agriculturae. 7:44-48. DOI:10.15192/PSCP.SA.2014.3.1.4448

Adenaike AS, Akpan U, Udoh JE, Wheto M, Durosaro SO, Sanda AJ & Ikeobi CON. 2017. Evaluation of growth functions in Nigerian chickens. Pertanika Journal of Tropical Agricultural Science. 40(4):611-620.

Aggrey SE. 2003. Comparison of three nonlinear and spline regression models for describing chicken growth curves. Poultry Science. 81:1782-1788.

Ait Kaki A & Moula N. 2013. Performances de production de la poule locale kabyle. Revue Agriculture. 5(1):1-4.

Becker S, Büscher W & Tiemann I. 2023. The British Ixworth: individual growth and egg production of a purebred dual-purpose chicken. British Poultry Science. 64(6):659-669. DOI:10.1080/00071668.2023.2245124

Bo HX, Hoa DV, Nhung DT, Hue DT & Luc DD. 2022. Nonlinear growth models for indigenous Vietnamese Ri chicken. Journal of Animal and Plant Sciences. 32(6):1535-1541. DOI:10.36899/JAPS.2022.6.0562

Bondoc OL. 2021. Grading and size classification of chicken eggs produced by native, egg-type, meat-type, dual-purpose and fancy-type breeds under Philippine conditions. International Journal of Poultry Science. 20(2):87-97. DOI:10.3923/ijps.2021.87.97

Boonkum W, Duangjinda M, Kananit S, Chankitisakul V & Kenchaiwong W. 2021. Genetic effect and growth curve parameter estimation under heat stress in slow-growing Thai native chickens. Veterinary Sciences. 8(12):297. DOI:10.3390/vetsci8120297

Brito C, Thainara J, Maciel L, Corassa A, Vargas Júnior J, Murilo G, Oliveira Júnior G, Silva C, Siqueira L, Débora C, De O & Carvalho. 2021. Growth curves of different free-range chicken lineages by the Gompertz model. Research, Society and Development. 10(5): e48610515014. DOI:10.33448/rsd-v10i5.15014

Burnham KP & Anderson DR. 2002. Model Selection and Inference: A Practical Information-Theoretic Approach. 2nd ed. New York: Springer-Verlag. DOI:10.1007/b97636

Chomchuen K, Tuntiyasawasdikul V, Chankitisakul V & Boonkum W. 2022. Genetic evaluation of body weights and egg production traits using a multi-trait animal model and selection index in Thai native synthetic chickens (Kaimook e-san2). Animals. 12(3):335. DOI:10.3390/ani12030335

Darmani Kuhi H, López S & France J. 2003. A comparative evaluation of functions for the analysis of growth in male broilers. Journal of Agricultural Science. 140:451-459. DOI:10.1017/S0021859603003149

Durosaro SO, Jeje OS, Ilori BM, Iyasere OS & Ozoje MO. 2021. Application of non-linear models in description of growth of dual purpose FUNAAB Alpha chickens. Journal of Agriculture and Rural Development in the Tropics and Subtropics. 122:147-158.

Eleroğlu H, Yıldırım A, Şekeroğlu A, Çoksöyler FN & Duman M. 2014. Comparison of growth curves by growth models in slow-growing chicken genotypes raised the organic system. International Journal of Agriculture and Biology. 16:529-535.

Ghaderi-Zefrehei M, Rafeie F, Zakizadeh S, Torshizi ME, Peters SO & Smith J. 2024. Genetic variance components of the growth curve for Isfahan indigenous chicken. Veterinary Medicine and Science. 10(2): e1388. DOI: 10.1002/vms3.1388. PMID: 38379342; PMCID: PMC10879718

Ghavi Hossein-Zadeh N. 2025. Application of alternative nonlinear models to predict growth curve in partridges. PLOS One. 20: e0321680. DOI: 10.1371/journal.pone.0321680

González Ariza A, Arando Arbulu A, Navas González FJ, Nogales Baena S & Delgado Bermejo JV. 2021. The study of growth and performance in local chicken breeds and varieties: a review of methods and scientific transference. Animals. 11(9):2492. DOI:10.3390/ani11092492

Kaplan S & Gurcan E. 2016. Comparison of growth curves using non-linear regression function in Japanese quail. Journal of Applied Animal Research. 46:1-6. DOI:10.1080/09712119.2016.1268965

Karaman E, Narinc D, Firat MZ & Aksoy T. 2013. Nonlinear mixed effects modeling of growth in Japanese quail. Poultry Science. 92(7):1942-1948. DOI:10.3382/ps.2012-02896

Koushandeh A, Chamani M, Yaghobfar A, Sadeghi A & Baneh H. 2019. Comparison of the accuracy of nonlinear models and artificial neural network in the performance prediction of Ross 308 broiler chickens. Poultry Science Journal. 7(2):151-161. DOI:10.22069/psj.2019.16690.1455

Kumar A, Kumar S, Pandey M, Chaudhari C, Aruna T, Meena R, Kanadkhedkar H, Chandrahas & Verma MR. 2022. Growth modelling in Aseel native chicken. Acta Scientific Veterinary Sciences. DOI:10.31080/ASVS.2022.04.0460

Loengbudnark W, Chankitisakul V & Boonkum W. 2025. Genetic perspectives on thermal tolerance in native chickens using non-linear growth models and temperature-humidity indices. Poultry Science. 104(9):105427. DOI: 10.1016/j.psj.2025.105427

Manav HR, Narinç D, Aygün A, Öksüz Narinç N, Kaya Başar E & Fırat MZ. 2026. Bayesian multi-model comparison and nonlinear mixed modelling of growth trajectories in Denizli chickens. Animals. 16(11):1-17.

Manjula P, Park HB, Seo D, Choi N, Jin S, Ahn S, Heo K, Kang B & Lee JH. 2017. Estimation of heritability and genetic correlation of body weight gain and growth curve parameters in Korean native chicken. Asian-Australasian Journal of Animal Sciences. 31. DOI:10.5713/ajas.17.0179

Mata-Estrada A, González-Cerón F, Pro-Martínez A, Torres-Hernández G, Bautista-Ortega J, Becerril-Pérez CM, Vargas-Galicia AJ & Sosa-Montes E. 2020. Comparison of four nonlinear growth models in Creole chickens of Mexico. Poultry Science. 99(4):1995-2000. DOI: 10.1016/j.psj.2019.11.031

Morgan PH, Mercer LP & Flodin NW. 1975. General model for nutritional responses of higher organisms. Proceedings of the National Academy of Sciences of the United States of America. 72(11):4327-4331.

Narinc D, Karaman E, Firat M & Aksoy T. 2010. Comparison of non-linear growth models to describe the growth in Japanese quail. Journal of Animal and Veterinary Advances. 9:1961-1966. DOI:10.3923/javaa.2010.1961.1966

Nawaz AH, Ding J, Ali M, Leng D, Mukhtar N, Ali A & Feng C. 2025. Decoding chicken growth regulation through multi-omics insights and emerging genetic tools for growth optimization. Poultry Science. 104(10):105542. DOI: 10.1016/j.psj.2025.105542

Ndri A, Koua B, Ahouchi V & Adepo-Gourene B. 2018. Body weight and growths curve parameters evaluation of three chicken genotypes (Gallus gallus domesticus) reared in claustration. Journal of Advanced Veterinary and Animal Research. 5. DOI:10.5455/javar. 2018.e265

Osaiyuwu O, Oyebanjo M, Coker O & Mabel A. 2024. Comparison of mathematical models describing the growth of tropically adapted Ross 308 commercial broiler chickens. Animal Research International. 21:5403-5414.

Plaengkaw S, Khumpeerawat P, Sukprasert C, Phongphanich P, Saowaphak P & Lokaewmanee K. 2026. Growth curve patterns in broilers and KU-Phuphan and Pradu Hang Dam chickens using nonlinear models. Tropical Animal Science Journal. 49(2):99. DOI:10.5398/tasj.2026.49.2.99

Posada SL, Gomez O & Rosero Noguera R. 2014. Application of the logistic model to describe the growth curve in dogs of different breeds. Revista MVZ Cordoba. 19:4015-4022. DOI:10.21897/rmvz.121

Pourhamidi S, Esmailizadeh A, Salarmoini M & Fozi MA. 2024. Comparison of productive performance of Marandi, White Leghorn, and Marandi-White Leghorn crossbred chickens. BMC Veterinary Research. 20(1):460. DOI:10.1186/s12917-024-04314-2

Rizzi C, Contiero B & Cassandro M. 2013. Growth patterns of Italian local chicken populations. Poultry Science. 92(8):2226-2235. DOI:10.3382/ps.2012-02825

Rodic V, Peric L, Đukić Stojčić M & Vukelić N. 2011. The environmental impact of poultry production. Biotechnology in Animal Husbandry. 27:1673-1679. DOI:10.2298/BAH1104673R

Roush W, Dozier W & Branton S. 2006. Comparison of Gompertz and neural network models of broiler growth. Poultry Science. 85:794-797. DOI:10.1093/ps/85.4.794

Saghi R & Saghi D. 2022. Estimation of heritability, phenotypic and genetic correlations for growth

curve characteristics of Japanese quail. Animal Science Research. 31(4):113-126. DOI:10.22034/as.2022.40879.1577

Scanes CG. 2025. General commentary: sexual dimorphism for juvenile body weight in lines of chickens selected for 8-week body weight. Frontiers in Physiology. 16:1607477. DOI:10.3389/fphys.2025.1607477

Şengül T, Çelik Ş, Şengül AY, İnci H & Şengül Ö. 2024. Investigation of growth curves with different nonlinear models and MARS algorithm in broiler chickens. PLOS One. 19(11): e0307037. DOI: 10.1371/journal.pone.0307037

Setiaji A, Lestari D, Ma'rifah B, Krismiyanto L, Agusetyaningsih I & Sugiharto S. 2023. Gompertz non-linear model for predicting growth performance of commercial broiler chickens. Journal of the Indonesian Tropical Animal Agriculture. 48:143-149. DOI:10.14710/jitaa.48.2.143-149

Setiaji A, Lestari DA, Pandupuspitasari NS, Agusetyaningsih I, Sutopo S, Tamaningrum TD, Philco SV, Alfaruq MN, Raza MA & Sugiharto S. 2025. Growth curve evaluation for Indonesian indigenous Red Kedu chicken by using non-linear models. Journal of Livestock Science and Technology. 14(1):1-7. DOI:10.22103/jlst.2025.24898.1607

Sharifi MA, Patil CS, Yadav AS & Bangar YC. 2022. Mathematical modeling for egg production and egg weight curves in a synthetic white leghorn. PMC. 8891992.

Sutherland DAT, Honaker CF, Dorshorst B, Andersson L, Brisbin IL Jr & Siegel PB. 2018. Growth patterns for three generations of an intercross between red junglefowl and chickens selected for low body weight. Journal of Animal Breeding and Genetics. DOI:10.1111/jbg.12336

Wen Y, Liu K, Liu H, Cao H, Mao H, Dong X & Yin Z. 2019. Comparison of nine growth curve models to describe growth of partridges (Alectoris chukar). Journal of Applied Animal Research. 47:195-200. DOI:10.1080/09712119.2019.1599900

Wu S, Chen Z, Zhou X, Lu J, Tian Y, Jiang Y, Liu Q, Wang Z, Li H, Qu L & Zhang F. 2024. Analysis of genetic diversity and genetic structure of indigenous chicken populations in Guizhou province based on genome-wide single nucleotide polymorphism markers. Poultry Science. 103(12):104383. DOI: 10.1016/j.psj.2024.104383

Xie WY, Pan NX, Zeng HR, Yan HC, Wang XQ & Gao CQ. 2020. Comparison of nonlinear models to describe the feather growth and development curve in yellow-feathered chickens. Animal. 14(5):1005-1013. DOI:10.1017/ s1751731 119003082

Yang Y, Mekki D, Lv S, Wang LY, Yu JH & Wang JY. 2006. Analysis of fitting growth models in Jinghai mixed-sex yellow chicken. International Journal of Poultry Science. 5:517-521. DOI:10.3923/ijps.2006.517.521

Yapi-Gnaore VC, Loukou EN, Konan J, Toure G, Kreman K, Youssao I, Kayang B, Rognon X & Tixier-Biochard M. 2011. Live weights and growth curve parameters of local chickens (Gallus domesticus) in Côte D'Ivoire. Agronomic Africanis. 23(3):273-281.

Zárate-Contreras D, González-Cerón F, Cuca-García JM, Pro-Martínez A, Ramírez-Valverde G, Aggrey SE, Hernández-Mendo O, Gallegos-Sánchez J & Sosa-Montes E. 2022. Mexican Creole chickens: effect of data collection periods on goodness-of-fit and parameter precision of growth models. Poultry Science. 101(7):101903. DOI: 10.1016/j.psj.2022.101903

Zhou Y, Liu J, Lei Q, Han H, Liu W, Li D, Sun Y, Hao D, Li F, Cao D & Wang J. 2025. Identification of quantitative trait loci and candidate genes associated with growth curve parameters in Chinese Wenshang barred chickens. Poultry Science. 104(2):104767. DOI: 10.1016/j.psj.2025.104767