



## Growth Curve Patterns in Broilers and KU-Phuphan and Pradu Hang Dam Chickens Using Nonlinear Models

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(Received 19-07-2025; Revised 04-12-2025; Accepted 05-12-2025)

### ABSTRACT

The growth performance of poultry is an important economic indicator and is crucial for the accurate modeling of growth curves, particularly for indigenous chicken breeds. Therefore, the optimal nonlinear growth model was investigated for commercial broilers and for two indigenous chicken breeds (KU-Phuphan and Pradu Hang Dam), breed-specific characteristics were delineated, and the influence was examined of sex on growth patterns. Chickens were weighed every 2 weeks. The broilers were followed for 6 weeks (fast-growing chickens) and the indigenous chickens (KU-Phuphan and Pradu Hang Dam) for 12 weeks (slow-growing chickens), with all groups analyzed for growth pattern using five nonlinear models. All models were evaluated for performance using  $R^2$ , RMSE, MAE, AIC, and BIC. The Gompertz model provided a better fit for the broilers, while the Hossfeld model was best for both indigenous breeds, with the models providing very good levels of prediction. The best-fitting models showed that growth parameters were different between breeds and between sexes. For example, in the indigenous breeds, the males had higher maximum body weight, cumulative weight gain, and growth rate than the females. However, there were no consistent sex differences in the broilers during their 6-week production period. There were only significant impacts of breed  $\times$  sex interaction at ages 2 and 4 weeks. Overall, the optimal models for predicting chicken growth were specific to each breed. This finding should be useful for making decisions about breeding, feeding, and managing native poultry production systems.

**Keywords:** body weight; breeding; broilers; growth; modeling

### INTRODUCTION

The global poultry industry is facing two major challenges: meeting the increasing demand for animal protein and protecting native genetic resources (Padhi, 2016). In Thailand, native chicken breeds, such as black-boned chickens, are important genetic resources because they have cultural importance and unique nutritional properties. However, still, there is little known about how these breeds grow compared to commercial broilers, which makes it hard to use them in modern production systems.

Black-boned chickens have melanin in their skin, meat, and bones. This gives them a unique biochemical profile that is high in melanin and carnosine, two substances that are known for their antioxidant properties (Fu *et al.*, 2022). Research has shown that it could be a functional food, especially in Asian markets (Khumpeerawat *et al.*, 2021). The KU-Phuphan and the Pradu Hang Dam breeds are important genetic resources in Thailand; however, there has been

insufficient research published on their growth pattern, especially for native chicken breeds.

Nonlinear growth models are mathematical equations that describe the variation in growth rate with age and body weight, where often, the growth rate is represented by a sigmoidal (S-shaped) curve, which represents the biological limit to growth (Narinç *et al.*, 2017). Nonlinear models describe the biological process by which growth increases over initial stages, reaches a maximum rate at an inflection point, and subsequently declines as the animal approaches its natural potential to reach maturity (asymptotic weight) (Gautam, 2024). In contrast, linear models assume that growth rates remain constant. These models convert unprocessed weight data into biologically important parameters, such as the asymptotic weight (A), growth rate constant (k), and inflection point ( $t^*$ ), which can be used for selective breeding and management practices (Selvaggi *et al.*, 2015). Although comprehensive research has determined the growth limits of commercial broiler chickens based on various models, such as Gompertz,

von Bertalanffy, and Weibull (Mata-Estrada *et al.*, 2020), there have been insufficient studies involving the native breeds of Southeast Asia.

One study on native chickens concluded that various breeds were best described using different models. For example, Nguyen *et al.* (2021) determined that the Richards model was optimal for Vietnamese Ri chickens, whereas Faraji-Arough *et al.* (2019) reported model-specific advantages for Iranian indigenous breeds. Mata-Estrada *et al.* (2020) found that some growth models offered improved results in specific chicken populations relative to others.

The current study hypothesized that the KU-Phuphan and Pradu Hang Dam breeds have unique growth patterns compared to commercial broilers, and that more pronounced sex differences were observed in slower-growing indigenous chickens (Nguyen *et al.*, 2021). Furthermore, the optimal growth function more accurately reflects the biological pattern of adult growth rate decline. Therefore, the current study aimed to determine the most appropriate nonlinear model for each breed based on estimating breed-specific growth parameters and assessing sex effects, to serve as an evidence-based reference tool for the development of breeding and management strategies in indigenous poultry systems.

## MATERIALS AND METHODS

### Experimental Animals, Housing, and Management

This research received approval from the Kasetsart University Institutional Animal Care and Use Committee (Approval No. ACKU67-CSC-005) and the National Research Council of Thailand Ethics Review Committee (NRCT Permit No. U1-10350-2565). Furthermore, the study adhered to established animal welfare protocols. Three cohorts of 100 birds (each cohort consisting of 50 males and 50 females) were utilized, namely, KU-Phuphan (KP), Pradu Hang Dam (PHD), and commercial broilers (Ross 308).

The chickens were raised in an open-house system at the Kasetsart University Sakon Nakhon Campus farm, Thailand, in accordance with Good Agricultural Practices (GAP, 2009). Throughout the study, each chicken was tagged with a wing clip (National Band & Tag Company; KY, USA) to allow for identification.

Chickens were housed in open cages measuring 1.4 meters wide, 1.5 meters long, and 2.5 meters high. The building was constructed of concrete blocks 0.5 meters high and covered with floor-to-ceiling wire mesh to promote ventilation and prevent disease from pathogens. Rice husks served as a bedding material to protect against heat and to absorb moisture on the floor. Separate plastic containers (Mitr Kasetphan Co., Ltd., Thailand) were used to store water and food for the chickens. Each container held enough food for 10 chickens.

The density of the broiler chickens was maintained at 0.1 square meters per bird, in accordance with the National Bureau of Agricultural Commodity and Food Standards (2017) requirements. Rice husks were used as a litter material to provide warmth for the chicks. A 100

W light bulb supplied heat during the initial 6 weeks post-hatching, which helped to promote growth and to decrease mortality.

Nutritional management followed a two-phase feeding program: during 0–4 weeks, chickens received a commercially manufactured pelleted diet, containing minimum values of 21% crude protein (CP) and 3,200 kcal/kg metabolizable energy (ME); during 5–12 weeks, chickens received a diet with a minimum of 18% CP and 3,200 kcal/kg ME. All diets met the nutritional requirements for growing chickens (National Research Council, 1994). Feed and water were replenished as needed. Vaccination protocols were implemented by farm veterinarians following standard Thai commercial broiler farm procedures. Management followed the National Bureau of Agricultural Commodity and Food Standards (2017).

The sample size was calculated utilizing the pwr package (Champely, 2020) in the R statistical program (R Core Team, 2024) based on the parameters: 1) three treatment groups: commercial broiler, PHD, and KP chickens; 2) effect size of 0.6; 3) significance level tested at 0.05; and (4) power level of 0.8. The minimum required sample size was 9.99 animals per group, rounded to 10 for practicality.

Body weight was obtained weekly during 0–12 weeks using a precision digital scale (Tanita KD-200; Tanita Corp.; Japan). The average daily gain was computed for the intervals 0–2, 0–4, 0–6, 0–8, 0–10, and 0–12 weeks. Outliers were identified via the Mahalanobis distance based on chi-square criteria.

### Statistical Analysis

Data on body weight during 0–12 weeks and mean daily increase values were examined for the intervals 0–2, 0–4, 0–6, 0–8, 0–10, and 0–12 weeks. Statistical analysis was conducted on growth parameters derived from the optimal model for each breed. Analysis was performed using the JASP software version 0.19.3 (JASP Team, 2024).

Two-way analysis of variance was applied with the main effects being chicken breed (commercial broiler, KP, PHD) and sex (male, female), including breed × sex interaction effects. Mean comparisons were performed using Tukey's honest significant difference test at the 95% confidence level, with significance tested at  $p < 0.05$ .

The statistical model used for data analysis was:

$$y_{ij} = \mu + B_i + S_j + (B \times S)_{ij} + e_{ij}$$

where  $y_{ij}$  was the observation of the  $i^{\text{th}}$  breed and  $j^{\text{th}}$  sex,  $\mu$  was the overall mean,  $B_i$  was the fixed effect of the  $i^{\text{th}}$  breed ( $i$  was broiler, KU-Phuphan, and Pradu Hang Dam),  $S_j$  was fixed effect of the  $j^{\text{th}}$  sex ( $j$  was male, female),  $(B \times S)_{ij}$  was interaction effect between  $i^{\text{th}}$  breed and  $j^{\text{th}}$  sex, and  $e_{ij}$  was random error term.

### Estimation of Growth Function Parameters

Individual growth curve parameter estimates were derived for all chickens using five nonlinear models (Gompertz, Logistic, von Bertalanffy, Hossfeld, Weibull) with the equations shown in Table 1. Each model was fit-

ted to body weight data from day 1 through to week 12 of age. Growth curve parameters for each model were estimated using the Levenberg-Marquardt algorithm via the nlsLM function of the minpack.lm package (Elzhov *et al.*, 2023) in the R software environment (R Core Team, 2024).

**Model Selection Criteria**

Each model’s performance and goodness-of-fit were evaluated using leave-one-out cross-validation (LOOCV), which is suitable for small sample sizes (James *et al.*, 2013). Leave-one-out cross-validation (LOOCV) involves applying N-1 samples for the training set and a single sample for the testing set, iterating until each observation has been used once as the test set (James *et al.*, 2013).

Prediction errors were calculated in each iteration to determine the metrics of performance, consisting of: coefficient of determination (R<sup>2</sup>); root mean square error (RMSE); mean absolute error (MAE); Akaike Information Criterion (AIC); and Bayesian Information Criterion (BIC), as presented in Table 2. The model with the highest R<sup>2</sup> and the lowest RMSE, MAE, AIC, and BIC values was considered the most accurate for predicting chicken body weight during 0–12 weeks.

**RESULTS**

**Body Weight Development Patterns**

The three chicken breeds demonstrated different growth trajectories (Table 3). The commercial broiler chickens had a rapid growth rate of 6 weeks, significantly faster than for the domestic breeds. Growth increased rapidly until week 4 and thereafter decreased as it reached maturity. Conversely, the KP and PHD chickens showed slower but consistent growth throughout the 12 weeks, eventually achieving similar final body weights, despite varying growth patterns. Throughout the study, the broilers had consistently higher body weights, especially from hatching to 6 weeks, averaging over 1,600 g, in contrast to the 588 g for the KP and 456 g for the PHD samples (Figure 1), highlighting the substantial growth advantage of commercial strains against indigenous breeds.

**Sexual Dimorphism in Growth Performance**

There were no significant sex differences in body weight in commercial broiler chickens during the 6 weeks. Conversely, the KP chicken demonstrated notable male-female disparities from 6 weeks of age

Table 1. Nonlinear growth equations and derived parameters for five nonlinear growth models used to establish growth curves for broiler, KU-Phuphan, and Pradu Hang Dam chickens

Model	Equation	TI	WI	MI
Gompertz	$y = A \times \exp(-b \times \exp(-k \times t))$	$\ln(b)/k$	$A/e$	$k \times WI$
Logistic	$y = A / (1 + b \times \exp(-k \times t))$	$\ln(b)/k$	$A/2$	$k \times WI/2$
von Bertalanffy	$y = A \times (1 - b \times \exp(-k \times t))^3$	$\ln(3b)/k$	$A \times 8/27$	$3k \times WI/2$
Hossfeld	$y = A \times (t^b / (k + t^b))$	$\left(\frac{(b-1)k}{(b+1)}\right)^{\frac{1}{b}}$	$A \left(\frac{b-1}{2b}\right)$	$A \frac{(b-1)(b+1)}{4b} \left(\frac{(b-1)c}{(b+1)}\right)^{\frac{1}{b}}$
Weibull	$y = A - b \times \exp(-k \times t^\lambda)$	$\left(\frac{(\lambda-1)}{k \times \lambda}\right)^{\frac{1}{\lambda}}$	$A - b \times \exp(-k \times TI^\lambda)$	$b \times (\lambda - 1) \times \left(\frac{(k \times \lambda)}{(\lambda - 1)}\right)^{\frac{1}{\lambda}} \times \exp\left(-\left(1 - \frac{1}{\lambda}\right)\right)$

Note: y = body weight (g) at age t; A = asymptotic weight (g); b = integration constant or shape parameter (Hossfeld); k = maturity rate; λ = shape parameter; t = age in weeks; TI = age at inflection point (weeks), WI = weight at the inflection point (g), MI = maximum increment (g/week), e = 2.71828.

Table 2. Goodness-of-fit criteria formulas used for nonlinear regression model evaluation

Goodness-of-fit criteria	Formula	References
Coefficient of Determination	$R^2 = 1 - \frac{SSE}{SST}$	Kvålseth (1985)
Root mean square error	$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n}}$	Chai & Draxler (2014)
Mean absolute error	$MAE = \frac{\sum_{i=1}^n  y_i - \hat{y}_i }{n}$	-
Akaike’s information criterion	$AIC = n * \ln\left(\frac{SSE}{n}\right) + 2k$	Akaike (1974)
Bayesian information criterion	$AIC = n * \ln\left(\frac{SSE}{n}\right) + k * \ln(n)$	Schwarz (1978)

Note: SSE = sum of square errors; SST = total sum of squares; n = number of observations; k = number of parameters; y<sub>i</sub> = observed value; ŷ<sub>i</sub> = predicted value.

( $p < 0.05$ ), with the males reaching 1,465 g at 12 weeks, while the females reached 1,153 g, reflecting a 27% advantage for males. The PHD chickens displayed a consistent pattern, with males significantly heavier than females from age 2 weeks ( $p < 0.05$ ); at 12 weeks, the males averaged 1,475 g, while the females averaged 1,126 g, showing a 31% advantage. Across all breeds, sexual dimorphism was negligible during early development (0–4 weeks) but increased significantly between 6 and 12 weeks (Table 3).

### Breed-Specific Growth Characteristics

There were significant breed effects in growth performance. The commercial broilers reached market weight in 5 weeks, whereas the KP and PHD chickens required the complete 12-week growth period to reach similar body weights. In addition, there were significant differences in the body weight among breeds ( $p < 0.05$ ) from hatching to 6 weeks, with the broilers consistently being the heaviest, followed by KP and PHD. No significant changes were observed between the KP and

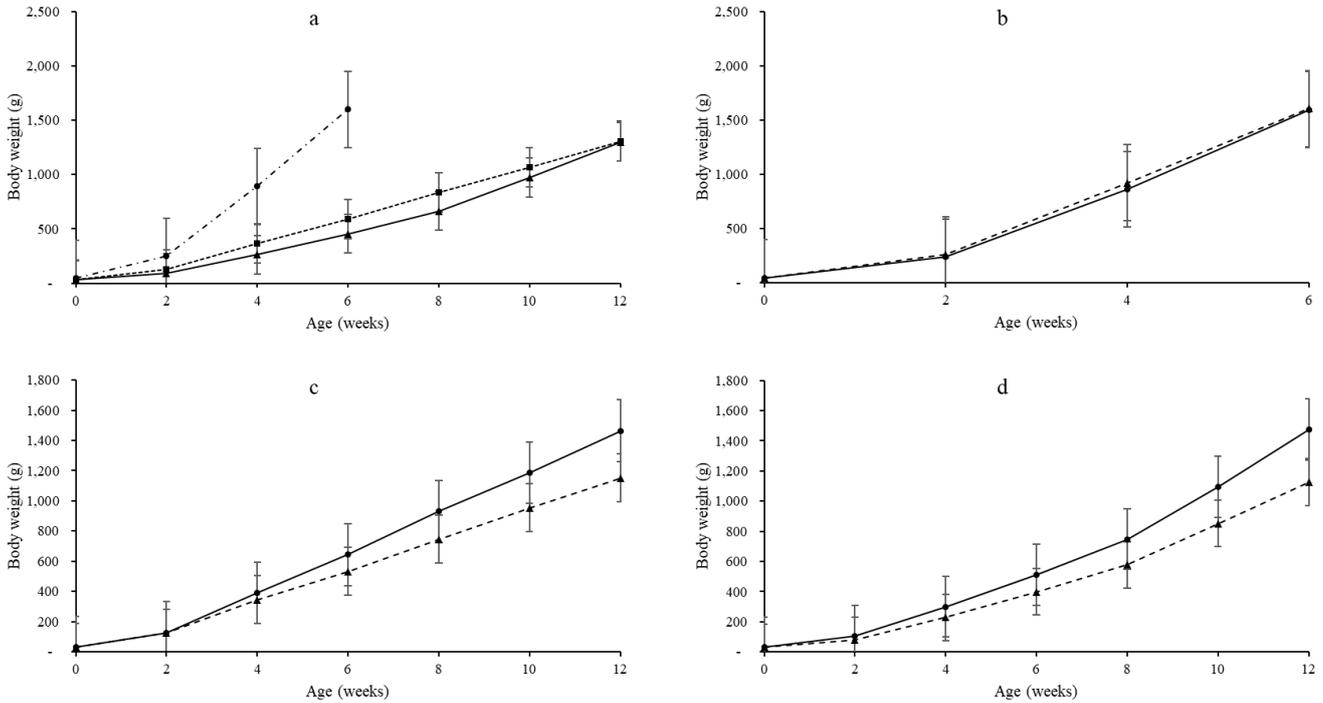


Figure 1. Average ( $\pm$  standard deviation) body weight progression over time in broiler, KU-Phuphan, and Pradu Hang Dam chickens (a). Growth curve patterns comparing male and female performance in (b) Broiler, (c) KU-Phuphan, and (d) Pradu Hang Dam chickens. Note: ---■--- = KU-Phuphan; —▲— = Pradu Hang Dam; -●- = Broiler; -▲- = Female; —●— = Male.

Table 3. Body weight and average daily gain of three chicken breeds (KU-Phuphan, Pradu Hang Dam, and broiler) at various ages and growth periods as influenced by breed, sex, and breed  $\times$  sex interaction

	Breed			SEM	Sex		SEM	P-value		
	Broiler	KP	PHD		Male	Female		Breed	Sex	Breed $\times$ Sex <sup>1</sup>
Age (weeks)	Body weight (g)									
0	47.5 <sup>b</sup>	31.0 <sup>a</sup>	32.0 <sup>a</sup>	1.848	36.7	37.0	1.509	<0.001	0.827	0.952
2	250 <sup>c</sup>	125 <sup>b</sup>	92 <sup>a</sup>	7.371	157	154	6.018	<0.001	0.662	0.012
4	892 <sup>c</sup>	369 <sup>b</sup>	264 <sup>a</sup>	22.538	517	499	18.402	<0.001	0.317	0.016
6	1599 <sup>c</sup>	588 <sup>b</sup>	456 <sup>a</sup>	35.483	917 <sup>b</sup>	845 <sup>a</sup>	28.971	<0.001	0.021	0.166
8	-	839 <sup>b</sup>	663 <sup>a</sup>	33.974	839 <sup>b</sup>	663 <sup>a</sup>	33.974	<0.001	<0.001	0.839
10	-	1070	973	52.144	1141 <sup>b</sup>	902 <sup>a</sup>	52.144	0.083	<0.001	0.917
12	-	1309	1301	54.181	1470 <sup>b</sup>	1140 <sup>a</sup>	54.181	0.877	<0.001	0.737
Age period (weeks)	Average daily gain (g/day)									
0–2	14.6 <sup>c</sup>	6.7 <sup>b</sup>	4.3 <sup>a</sup>	0.548	8.6	8.4	0.447	<0.001	0.768	0.017
0–4	30.2 <sup>c</sup>	12.0 <sup>b</sup>	8.4 <sup>a</sup>	0.825	17.2	16.4	0.673	<0.001	0.246	0.024
0–6	37.0 <sup>c</sup>	13.5 <sup>b</sup>	10.1 <sup>a</sup>	0.827	21.1 <sup>b</sup>	19.2 <sup>a</sup>	0.675	<0.001	0.011	0.165
0–8	-	14.5 <sup>b</sup>	11.2 <sup>a</sup>	0.592	14.4 <sup>b</sup>	11.3 <sup>a</sup>	0.592	<0.001	<0.001	0.868
0–10	-	14.8	13.6	0.742	15.9 <sup>b</sup>	12.5 <sup>a</sup>	0.742	0.125	<0.001	0.791
0–12	-	15.2	15.0	0.620	16.9 <sup>b</sup>	13.3 <sup>a</sup>	0.620	0.751	<0.001	1.000

Note: SEM = Standard error of means; <sup>1</sup>Interaction of breed and sex; <sup>a,b,c</sup> Means within a row and effects with different superscripts are significantly different ( $p < 0.05$ ). KP= KU-Phuphan; PHD= Pradu Hang Dam.

PHD chickens beyond 8 weeks (Table 3). The interaction effects of breed and sex were significant at 2 and 4 weeks, but not at subsequent ages.

**Average Daily Gain (ADG)**

This study found that breed and sex significantly affected the ADG (Table 3). The commercial broilers showed rapid growth during the first 6 weeks, consistent with the intensive selection program that had aimed at achieving early weight gain and increasing efficiency in commercial production. Conversely, the KP and PHD chickens exhibited a continuous and consistent increase in ADG, suggesting different metabolic mechanisms suited to resource-limited environments.

Sexual dimorphism in ADG became increasingly evident with age in the indigenous breeds, as males consistently outperformed females from mid-development forward ( $p < 0.05$ ), suggesting hormone-driven growth responses approaching sexual maturity. Conversely, the commercial broilers displayed no significant sexual dimorphism during their growth period, indicating that the emphasis on rapid early growth may have diminished sex-specific differentiation. The eventual convergence of ADG for the KP and PHD samples in later phases indicated similar genetic potential, despite divergent initial trajectories, potentially signifying compensatory expansion in the slower-starting PHD line.

**Growth Model Performance Comparison**

A comparative analysis of the five growth models revealed significant correlations of specific functions between breeds (Table 4). The Gompertz model was the most appropriate for broiler chickens, providing the highest predictive performance ( $R^2 = 0.999$ , AIC = 68.13, BIC = 67.92), followed by the Weibull model. In contrast for the two indigenous chicken breeds, the Hossfeld model provided the most appropriate

predictive performance (KP chickens:  $R^2 = 0.999$ , AIC = 115.15, BIC = 117.41; and PHD chickens:  $R^2 = 0.999$ , AIC = 115.73, BIC = 117.99), while the logistic model provided the poorest performance modeling across all breeds, indicating that this model still had limitations in its application to these chicken populations.

Investigation of breed, sex, and their interaction effects revealed significant differences across several growth curve variables (Table 5). The age at the inflection point (TI) demonstrated highly significant breed effects ( $p < 0.001$ ), with the PHD chickens having the highest values; however, sex effects were mostly not significant. On the other hand, weight at the inflection point (WI) and maximum increment (MI) were significantly different at high levels for both breed ( $p < 0.001$ ) and sex ( $p < 0.01$ ), with the males being generally heavier and having a greater maximum growth rate than the females.

The main growth curve characteristics indicated that there were significant variations in asymptotic weight (A) depending on breed and sex, with the broilers having the highest values (Table 5). In addition, the maturation rate (k) differed among breeds, with the broilers maturing the fastest. Sexual dimorphism was consistent across breeds, with the males attained higher asymptotic weights and maximum increments, whereas females reached their inflection points earlier.

**DISCUSSION**

Based on the results of the current study, there were divergent growth patterns between the commercial broilers and the two indigenous Thai chicken breeds, impacting production techniques and market strategy. The commercial broilers attained a weight of 1,600 g at 6 weeks, in contrast to the 588 g for the KP and 456 g for the PHD chickens, illustrating the positive impact of the extensive genetic selection for increased growth in modern strains (Gautam, 2024). These results aligned with another study indicating that commercial broilers

Table 4. Goodness of fit comparison of growth curve models for body weights in male and female broilers, KU-Phuphan, and Pradu Hang Dam chickens

Breeds	Models	R <sup>2</sup>	MAE	RMSE	AIC	BIC
Broiler	Gompertz	0.999	15.82	17.75	68.13	67.92
	Logistic	0.998	18.66	22.35	71.36	71.14
	von Bertalanffy	0.998	20.24	23.31	71.95	71.73
	Hossfeld	0.999	18.86	21.11	70.56	70.35
	Weibull	0.999	12.89	16.33	68.97	68.70
KU-Phuphan	Gompertz	0.998	17.05	20.46	123.37	125.63
	Logistic	0.993	31.04	36.10	138.14	140.40
	von Bertalanffy	0.999	12.47	15.46	116.09	118.35
	Hossfeld	0.999	12.29	14.91	115.15	117.41
	Weibull	0.999	12.77	15.45	118.06	120.89
Pradu Hang Dam	Gompertz	0.998	16.51	18.68	121.01	123.27
	Logistic	0.996	22.79	26.96	130.54	132.80
	von Bertalanffy	0.999	13.49	15.71	116.50	118.76
	Hossfeld	0.999	12.87	15.25	115.73	117.99
	Weibull	0.999	12.63	14.71	116.80	119.63

Note: R<sup>2</sup> = Coefficient of determination; MAE = mean absolute error; RMSE = Root mean square error; AIC = Akaike's information criterion; BIC = Bayesian information criterion.

Table 5. Comparison of growth curve parameters estimated by Gompertz, Logistic, Von Bertalanffy, Hossfeld, and Weibull models in broiler, KU-Phuphan, and Pradu Hang Dam chickens classified by breed, sex, and their interactions

Model	Parameter <sup>1</sup>	Breed			SEM	Sex		SEM	P-value		
		Broiler	KP	PHD		Male	Female		Breed	Sex	Breed×Sex <sup>2</sup>
Gompertz	A	3257 <sup>b</sup>	1825 <sup>a</sup>	3781 <sup>b</sup>	191	3340 <sup>b</sup>	2569 <sup>a</sup>	156	<0.001	0.002	0.323
	b	6.62 <sup>b</sup>	4.61 <sup>a</sup>	5.02 <sup>a</sup>	0.12	5.48	5.36	0.09	<0.001	0.399	0.165
	k	0.33 <sup>c</sup>	0.21 <sup>b</sup>	0.12 <sup>a</sup>	0.01	0.21	0.23	0.01	<0.001	0.191	0.378
	TI	5.89 <sup>a</sup>	7.53 <sup>b</sup>	13.33 <sup>c</sup>	0.41	9.23	8.60	0.33	<0.001	0.198	0.971
	WI	1198 <sup>b</sup>	671 <sup>a</sup>	1391 <sup>b</sup>	70.51	1228 <sup>b</sup>	945 <sup>a</sup>	57.57	<0.001	0.002	0.323
Logistic	MI	381 <sup>c</sup>	135 <sup>a</sup>	166 <sup>b</sup>	7.02	245 <sup>b</sup>	210 <sup>a</sup>	5.73	<0.001	<0.001	0.390
	A	2012 <sup>b</sup>	1447 <sup>a</sup>	1870 <sup>b</sup>	60	1950 <sup>b</sup>	1603 <sup>a</sup>	49	<0.001	<0.001	0.031
	b	77.56 <sup>c</sup>	26.51 <sup>a</sup>	38.80 <sup>b</sup>	2.34	49.64	45.61	1.91	<0.001	0.150	0.427
	k	0.81 <sup>c</sup>	0.41 <sup>b</sup>	0.34 <sup>a</sup>	0.01	0.52	0.53	0.01	<0.001	0.622	0.439
	TI	5.48 <sup>a</sup>	7.98 <sup>b</sup>	10.59 <sup>c</sup>	0.17	8.13	7.90	0.14	<0.001	0.275	0.681
Von Bertalanffy	WI	970 <sup>b</sup>	723 <sup>a</sup>	934 <sup>b</sup>	40.59	975 <sup>b</sup>	777 <sup>a</sup>	33.14	<0.001	<0.001	0.341
	MI	391 <sup>b</sup>	147 <sup>a</sup>	160 <sup>a</sup>	11.97	254 <sup>b</sup>	212 <sup>a</sup>	9.78	<0.001	0.005	0.989
	A	6485 <sup>a</sup>	2285 <sup>a</sup>	13151 <sup>b</sup>	1552	8136	6478	1267	<0.001	0.364	0.891
	b	1.03 <sup>b</sup>	0.89 <sup>a</sup>	0.90 <sup>a</sup>	0.01	0.94	0.94	0.01	<0.001	0.925	0.103
	k	0.16 <sup>b</sup>	0.13 <sup>b</sup>	0.05 <sup>a</sup>	0.01	0.10	0.12	0.01	<0.001	0.122	0.362
Hossfeld	TI	7.59 <sup>a</sup>	7.55 <sup>a</sup>	23.55 <sup>b</sup>	1.63	13.38	12.42	1.33	<0.001	0.621	0.941
	WI	1921 <sup>a</sup>	676 <sup>a</sup>	3896 <sup>b</sup>	460	2410	1919	375	<0.001	0.365	0.891
	MI	408 <sup>c</sup>	130 <sup>a</sup>	226 <sup>b</sup>	16.46	279 <sup>b</sup>	231 <sup>a</sup>	13.44	<0.001	0.019	0.888
	A	4142	2834	4479	693	4383	3084	560	0.264	0.074	0.354
	b	2.67 <sup>b</sup>	1.93 <sup>a</sup>	1.79 <sup>a</sup>	0.07	2.16	2.17	0.06	<0.001	0.340	0.390
Weibull	k	268	150	249	34	265 <sup>b</sup>	170 <sup>a</sup>	27	0.071	0.022	0.345
	TI	5.91 <sup>a</sup>	8.08 <sup>b</sup>	8.65 <sup>b</sup>	0.51	8.02	7.07	0.42	<0.001	0.135	0.788
	WI	1212 <sup>b</sup>	745 <sup>a</sup>	724 <sup>a</sup>	80	1020 <sup>b</sup>	767 <sup>a</sup>	65	<0.001	0.012	0.788
	MI	366 <sup>b</sup>	130 <sup>a</sup>	114 <sup>a</sup>	8.47	218 <sup>b</sup>	189 <sup>a</sup>	6.92	<0.001	0.007	0.451
	A	2269 <sup>a</sup>	3314 <sup>a</sup>	32010 <sup>b</sup>	2627	17399 <sup>b</sup>	7663 <sup>a</sup>	2226	<0.001	0.005	0.003
Weibull	b	2233 <sup>a</sup>	3326 <sup>a</sup>	31994 <sup>b</sup>	2627	17383 <sup>b</sup>	7652 <sup>a</sup>	2226	<0.001	0.005	0.003
	k	0.005 <sup>a</sup>	0.011 <sup>b</sup>	0.001 <sup>a</sup>	0.000	0.004 <sup>a</sup>	0.007 <sup>b</sup>	0.000	<0.001	0.026	0.290
	λ	2.90 <sup>b</sup>	1.75 <sup>a</sup>	1.88 <sup>a</sup>	0.088	2.21	2.14	0.072	<0.001	0.521	0.377
	TI	5.64	9.55	44.13	3.28	23.98	15.57	2.68	<0.001	0.037	0.071
	WI	1104 <sup>a</sup>	1001 <sup>a</sup>	11611 <sup>b</sup>	990	6326 <sup>b</sup>	2818 <sup>a</sup>	808	<0.001	0.005	0.003
Weibull	MI	387 <sup>b</sup>	133 <sup>a</sup>	330 <sup>b</sup>	19.04	327 <sup>b</sup>	240 <sup>a</sup>	15.55	<0.001	<0.001	0.004

Note: <sup>1</sup> KP = KU-Phuphan; PHD = Pradu Hang Dam; A = asymptotic weight (g); b = integration constant or shape parameter (Hossfeld); k = maturity rate; λ = shape parameter; TI = age at inflection point (weeks), WI = weight at the inflection point (g), MI = maximum increment (g/week); <sup>2</sup> Breed×Sex = breed and sex interaction; <sup>a,b,c</sup> Means within a row and effects with different superscripts are significantly different (p<0.05).

attained superior early growth rates compared to indigenous breeds, attributable to decades of selection for enhanced weight gain and feed efficiency (Soglia *et al.*, 2020).

At age 12 weeks, the body weight of the KP chickens (1,309 g) was competitive compared to other indigenous breeds. Native chickens, although having a slower growth rate, have advantages in disease resistance, environmental adaptation, and meat quality that are favored in niche markets (Franzoni *et al.*, 2021). The results of the current study indicated significant differences between breeds in terms of growth rate and the time it took to reach market weight (1,200–1,300 g). Specifically, commercial broilers reached this weight in 5 weeks, while KP and PHD took 12 weeks, indicating a balance between quick growth and effective environmental adaptability. Furthermore, this pattern aligned with the findings associated with other slow-growing indigenous chickens globally, which commonly require 12–16 weeks to reach their market weight (Swati *et al.*, 2025). These reported growth patterns across breeds likely reflect genetic variations caused by distinct breeding purposes, despite the

current study applying uniform environmental, dietary, and managerial circumstances.

In native chickens, increasing age produced significant growth differences between males and females, suggesting a sex-specific pattern. This was consistent with other research that found that the males of several poultry species weighed more than the females (Franzoni *et al.*, 2021; Gautam, 2024). In the current study, during the 0–6 week growth period, commercial broilers did not show significant differences in body weight and ADG between the sexes, suggesting that selection for rapid growth may reduce sex-dependent growth differences. In contrast, with the indigenous chickens, the males generally outperformed the females in terms of body weight and ADG, suggesting that sex had influenced growth performance, particularly as body weight neared market weight. This breed-specific pattern likely indicated different hormonal regulation and energy allocation strategies, with females focusing on reproductive development while males allocate resources to somatic growth (Faraji-Arough *et al.*, 2019).

At age 10–12 weeks, the KP and PHD chickens had similar body weights, indicating that PHD

chickens showed compensatory growth in earlier stages to overcome initial setbacks (Chaikuad *et al.*, 2022), illustrating the potential for specific nutritional strategies during essential growth phases in native breeds. The growth patterns specific to breeds indicate the importance of customized feeding programs that correspond to physiological requirements during various developmental stages. Growth curve modeling demonstrated that the Gompertz function most accurately represented broiler performance, consistent with prior validations of its success in describing the sigmoidal growth trajectory of commercial broiler, which is marked by rapid early gains followed by a deceleration as maturity is approached (Narinç *et al.*, 2017; Gautam, 2024; Şengül *et al.*, 2024).

The Hossfeld model demonstrated superior performance relative to other growth functions for the Thai native breeds (KP and PHD), contrasting with the patterns observed in the commercial chickens. This indicated breed-specific genetic and physiological characteristics, as the native chickens demonstrated slower and more complex growth patterns, which were more accurately represented by the Hossfeld model (Chaikuad *et al.*, 2022). The logistic model demonstrated consistently low performance across all breeds, as other published literature indicates its propensity to overestimate initial weights and underestimate final weights, which decreases predictive accuracy (Mata-Estrada *et al.*, 2020; Nguyen *et al.*, 2021). Growth models provide biologically interpretable parameters that improve prediction, nutritional optimization, and breeding evaluation, thus serving as essential tools for precision poultry management (Narinç *et al.*, 2017).

The genetic improvement process results in unique characteristics for each chicken line, which is a result of the selection objectives. Broiler chickens undergo intensive selection, focusing on cost reduction, growth acceleration, and feed efficiency. In contrast, indigenous chickens exhibit a more gradual and natural growth pattern, indicating that their development is influenced by natural selection related to environmental factors (Soglia *et al.*, 2020; Franzoni *et al.*, 2021). This observed variation influences production strategies, including management, market weight, and feeding protocols. The PHD breed exhibits favorable growth traits in contrast to indigenous chickens, suggesting their viability for meat production (Mookprom *et al.*, 2021). In the current study, the parameters of growth varied according to sex, with males demonstrating superior weights and growth rates, whereas females typically reached sexual maturity at a later point in their development. The discerned patterns revealed clear distinctions in energy distribution; females prioritize reproductive development, while males concentrate on the enhancement of body and muscle mass (Faraji-Arough *et al.*, 2019).

The current study provided comparative data on the growth performance of commercial broilers and two major Thai indigenous chicken breeds under controlled conditions. Furthermore, appropriate mathematical modeling of their growth trajectories could support informed decisions on nutrition, management, and marketing (Narinç *et al.*, 2017). Broilers have high

growth performance and are therefore suitable for intensive production systems that focus on rapid production yields. In contrast, native chickens, despite their slower growth, have potential for niche markets due to their excellent flavor and meat quality, and their consistency with traditional and sustainable production values, particularly in Thailand (Franzoni *et al.*, 2021). Future research should focus on optimizing indigenous production systems, clarifying genetic and other factors affecting growth, and developing selection strategies that increase production efficiency while maintaining traits valuable to smallholder and niche markets.

### Implications

The current study has provided important information to guide breeding strategies and production management in Thai native chickens in tropical environments. The growth pattern analysis supports body weight prediction at different ages and guides the development of breed- and sex-specific feeding programs for native chickens. The observation that model fit varies among breeds indicates the need for breed-specific approaches. The Hossfeld model can be used as a tool for predicting growth patterns and planning production in Thai native chickens. Selective breeding of native chickens is essential for increasing production efficiency while maintaining their unique characteristics, which helps preserve biodiversity and ensure nutritious foods.

### CONCLUSION

This study revealed complex growth patterns across multiple chicken breeds, indicating that generic solutions are insufficient. The Gompertz model was effective for commercial broilers but was ineffective for indigenous chickens such as the KU-Phuphan and Pradu Hang Dam breeds, indicating the need for more specialized models. The notable differences in growth traits help to provide an essential understanding of body weight, maturation speed, and developmental phase between breeds. The native breeds exhibited significant sex differences, although the commercial broilers shared similar traits in this area. These findings highlighted the importance of understanding breed-specific developmental traits and emphasized the importance of biodiversity conservation and sustainable practices in chicken production systems.

### CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

### DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

The authors declare that generative AI and AI-assisted technologies were used in this manuscript

preparation solely to improve readability and language clarity. All AI-assisted tools were applied under human oversight and control, with the authors maintaining full responsibility for the scientific content, data analysis, and interpretation of results.

### ACKNOWLEDGEMENT

This study was funded by the Research Grant for New Researcher Development, Kasetsart University, 2024 (Project Code: YF(KU)48.67), from the Kasetsart University Research and Development Institute (KURDI), Bangkok, Thailand. The authors gratefully acknowledge the technical assistance of the animal care staff at Kasetsart University Chalermphrakiat Sakon Nakhon Province Campus and the cooperation of local chicken breed conservation groups in providing breeding stock.

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