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Modeling Growth Curves to Estimate the Suitable Slaughter Ages for Tien Yen Female Chickens Raised by Different Diets

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Abstract

This study aimed to find the best model to describe the growth of Tien Yen female chickens and predict their live weight, weight gain, and suitable slaughter age. The body weights of 180 female chickens were measured every week from birth to 24 weeks of age. The chickens of the control group were fed a diet lower in protein and fiber. The chickens of the treatment group were fed a diet higher in protein and fiber. The data for growth performance were analyzed in R using six mathematical functions (von Bertalanffy, Janoschek, Gompertz, Logistic, Lopez, and Richards). The best models to describe the growth of Tien Yen females were Janoschek for the control group and Richards for the treatment group. The maximum absolute weekly gains occurred at 10 and 11 weeks of age (at the reflection point of the growth curves) and the maximum average weekly gains were obtained at 13.39 and 14.62 weeks of age for the control group and treatment group, respectively. Under the current local market conditions, the estimated economically optimal slaughter ages were 14.33 weeks (1,392.89g) for the control group and 15.17 weeks (1,565.23g) for the treatment group.

Keywords

Bodyweight, chicken, growth performance, mathematical function, slaughter age

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Introduction

In Vietnam, the chicken farming sector is vital to the economy, with the annual production of chicken meat (8.3 thousand tons) second only after pork (GSO, 2023). The diversity of indigenous chickens in Vietnam is remarkable with about 21 breeds (MARD, 2016). The importance of indigenous breeds in Vietnamese livestock has been confirmed in recent years and these animals represent an integral part of the country's conservation program (MARD, 2021). Vietnam's livestock development strategy for the period of 2021-2030 is to exploit and sustainably develop indigenous chicken genetic resources, promoting advantages and creating specific products for each region (MARD, 2020).

Tien Yen is one of the 21 important indigenous chicken breeds of Vietnam, and this breed originates in the North of Vietnam (MADR, 2016). From 2012 until now, the government has continuously provided financial support and research to develop and increase the scale of raising the Tien Yen chicken breed (DARD, 2022). Tien Yen chicken production has played an important role in improving the livelihoods of farmers. However, the development of Tien Yen chicken farming has encountered difficulties (Vu Dinh Ton *et al.*, 2021). The status of indigenous chicken breeds in Vietnam is vulnerable due to low production capacity, and along with this, shortages in knowledge about husbandry practices and livestock management (Nguyen Van Duy, 2022). Tien Yen chickens are raised in households that lack an understanding of poultry management. The cycle of raising chickens to slaughter is long, with Tien Yen female chickens taking up to 24-25 weeks (Hoang Xuan Truong, 2012). This long cycle of raising has reduced the breeding efficiency of Tien Yen chickens (Vu Dinh Ton *et al.*, 2021).

The growth curves of chickens have been investigated in Vietnam (Moula *et al.*, 2011; Nguyen Hoang *et al.*, 2021; Bo *et al.*, 2022; Tuan *et al.*, 2022), Italy (Rizzi *et al.*, 2013; Selvaggi *et al.*, 2015), Ghana (Osei-Amponsah *et al.*, 2014), and China (Yang *et al.*, 2006). The Gompertz function has been used to predict live weight and weight gain of Ri chickens in Vietnam as investigated by Moula *et al.* (2011) and Bo *et al.* (2022). Additionally, these studies used the non-linear model to determine which growth function was most suitable for estimating the live weights of animals. According to our knowledge, there have been no published papers investigating mathematical tools to describe the growth and to estimate the suitable slaughter ages for Tien Yen female chickens in Vietnam. Females of the Tien Yen chicken breed generally display significantly lower body weights than males, suggesting that sex-specific rearing practices may contribute to improved growth performance (Nguyen Hoang *et al.*, 2021). In practice, Tien Yen females are predominantly utilized for egg production, whereas the males are favored for meat. Male chickens are typically castrated at around 45 days of age (Vu Dinh Ton *et al.*, 2024) and subsequently reared for an extended period, often exceeding 30 weeks, before being marketed. Therefore, the present study aimed to enhance understanding of the management strategies for Tien Yen female chickens, with a focus on identifying appropriate dietary regimens, and determining the optimal slaughter age using different mathematical functions for describing the growth of Tien Yen female chickens fed different diets under household conditions in northern Vietnam.

Materials and Methods

This study investigated Tien Yen chickens raised under household conditions in Tien Yen district, Quang Ninh province, Vietnam. Tien Yen is situated in the northeast of Quang Ninh province, about 80km from both Ha Long city and Mong Cai city, and 255km from Hanoi. The region lies at 0-100m above sea level, with a humid subtropical climate and four distinct seasons. The average annual temperature is 22.4°C, with approximately 1,700 hours of sunshine (GSO, 2023). The experiment was conducted from January to December 2021, focusing on the growth performance of female Tien Yen chickens from hatchlings to 24 weeks of age. A total of 500 one-day-old chicks were reared under uniform feeding conditions from day 1 to 12 weeks of age (90 days) (**Table 1**).

At 91 days of age, 180 healthy female Tien Yen chickens were selected based on their initial weights, had their wings clipped, and then were randomly divided into two groups. There were 3 replicates for each of two groups with 90 chickens in each group. The groups used different diets (**Table 2**). The chickens of the control group were fed local feed resources,

Table 1. Ingredient composition of feed for female Tien Yen chicks from 1 day-old to 12 weeks of age

Ingredients (%)	Proportion	
	1-28 days	29-90 days
Poultry vitamix (CM1976)	0.10	0.10
Corn	62.90	68.50
DDGS	2.00	1.00
Premix	0.88	0.86
Sodium bicarbonate 99%	0.05	0.10
Choline chloride 60%	0.05	0.05
Salinomycin 12%	0.05	0.00
Poultry minemix (CM4089)	0.13	0.13
Basa fish oil	1.20	1.22
Soybean meal	23.87	18.82
Meat and bone meal	0.57	2.00
Limestone power	1.40	1.2
Dicalcium phosphate (DCP 17%)	0.73	0.12
Salt powder (NaCl)	0.29	0.21
Canola	0.00	0.00
Lysine 70%	0.60	0.46
L-met pro (Methionine 90%)	0.18	0.20
Wheat DDGS	3.00	1.00
Rapeseed meal	2.00	4.00
Threonine. L 98%	0.00	0.03
Analytical composition	Percentage (%)	
Crude protein (%)	21.50	19.00
Calcium	1.50	0.80
Phosphorus	1.00	0.50
Fiber	5.00	5.00
Metabolizable energy (kcal kg^{-1} DM)	3000	3030

which consisted of 75% agricultural products (70% yellow corn and 5% rice bran) and 25% commercial feed, resulting in a diet lower in protein and fiber (**Table 2**). The chickens of the treatment group were fed the treatment diet, which consisted of 69.2% agriculture products (55% yellow corn, 5% wheat bran, and 9.2% rice bran), 25% soybean meal, and 5.8% targeted nutrient supplements (limestone powder (2%), DCP (1%), mineral premix (1%), DL-Methionine (0.5%), NaCl (0.3%), L-Lysine (0.5%), and L-Threonine (0.5%)), resulting in a diet higher in protein and fiber (**Table 2**).

The feed compositions were analyzed at the Central Laboratory, Faculty of Animal Science, Vietnam National University of Agriculture. The nutrient contents were determined following Vietnamese standards: dry matter (TCVN 4326:2001), crude protein (TCVN 4328:2007), calcium (TCVN 1526:2007), phosphorus (TCVN 1525:2001), lipids (TCVN 4331:2001), and crude fiber (TCVN 4329:2007).

All the experimental broilers were raised in the same housing system with the floor of the housing covered with rice husks and access to “garden enhancements”. Feed and water were offered *ad libitum*, and the birds could go to the garden freely. The density was five chickens per square meter of floor area in the housing and one bird per square meter in the playground.

Table 2. Ingredient composition of feeds for female Tien Yen chickens from 13 to 24 weeks of age

Feed ingredients	Diets	
	Control group (%)	Treatment group (%)
Yellow corn	70	55
Soybean meal	0	25
Wheat bran	0	5
Rice bran	5	9.2
Limestone powder	0	2
DCP	0	1
Mineral premix	0	1
DL-Methionine 98 %	0	0.5
NaCl	0	0.3
L-Lysine HCl	0	0.5
L-Threonine	0	0.5
Commercial animal feed	25	0
Analytical composition		
DM	86.6	87.0
CP	10.9	16.3
Lipids	5.7	5.35
CF	2.4	4.5
Ca	0.2	0.9
P	0.5	0.8

Each chicken was individually identified using numbered plastic leg and wing bands. Body weight (BW) was recorded weekly on a fixed schedule using an electronic scale with a precision of 0.01g, up to five weeks of age. From 6 to 24 weeks of age, we used a mechanical balance (accuracy 5g).

The growth curves were analyzed in R software (R version 4.2.2, R Core Team (2022)). Six functional models, namely von Bertalanffy (Von Bertalanffy, 1957), Janoschek (Wellock *et al.*, 2004), Gompertz (Gompertz, 1825), Logistic (Pearl, 1977), Lopez (López *et al.*, 2000), and Richards (Richards & Kavanagh, 1945), were used for describing the growth of Tien Yen female chickens (**Table 3**). The BWs were estimated every week from birth to 24 weeks of age using the best models for each group. The slaughter age determination of 24 weeks for Tien Yen female chickens was informed by local knowledge pertaining to the breed's growth characteristics. This decision reflected an empirical understanding of Tien Yen female chicken development within the local context.

The six nonlinear models were fitted using the nlsLM() function from the minpack.lm package (Elzhov *et al.*, 2016) in R for each group. The key estimated parameters included asymptotic body weight (α), growth rate (k), inflection point (β), and shape parameter (m).

Model performance was evaluated using the Akaike information criterion (AIC), Bayesian information criterion (BIC), and coefficient of determination (R^2). AIC and BIC were computed using the AIC() and BIC() functions, with lower values indicating better model fit. While AIC prioritizes predictive accuracy, BIC emphasizes model correctness (Chakrabarti & Ghosh, 2011). The best-fitting model was identified based on the lowest AIC/BIC and highest R^2.

Predicted body weights were obtained using the predict() function. Absolute weekly gain ($WG_t = BW_t - BW_{t-1}$) was derived from the first derivative of the Janoschek function (control

Table 3. The details of the different nonlinear growth models

No.	Function	Equation	The first derivative of the growth function (WGt)	The average weekly gain (AWGt)
1	von Bertalanffy	$BW_t = \alpha \times (1 - \beta \times e^{-kt^3})$	$3\alpha k\beta t^2 e^{-kt^3}$	$\frac{\alpha\beta(1-e^{-kt^3})}{t}$
2	Janoschek	$BW_t = \alpha - (\alpha - BW_0) \times e^{-kt^m}$	$(\alpha - BW_0)kmt^{(m-1)}e^{-kt^m}$	$\frac{(\alpha - BW_0)(1 - e^{-kt^m})}{t}$
3	Gompertz	$BW_t = \alpha e^{-\beta e^{-kt}}$	$\alpha k\beta e^{-kt}e^{-\beta e^{-kt}}$	$\frac{\alpha(e^{-\beta e^{-kt}} - e^{-\beta})}{t}$
4	Logistic	$BW_t = \frac{\alpha}{1 + \frac{\alpha - BW_0}{BW_0} \times e^{-kt}}$	$\frac{\alpha(\frac{\alpha - BW_0}{BW_0})ke^{-kt}}{(1 + \frac{(\alpha - BW_0)}{BW_0}e^{-kt})^2}$	$\frac{(\alpha - BW_0)(1 - e^{-kt})}{t(1 + \frac{(\alpha - BW_0)}{BW_0}e^{-kt}}$
5	Lopez	$BW_t = \frac{(BW_0 \times \beta^k + \alpha \times t^k)}{(\beta^k + t^k)}$	$\frac{(\alpha - BW_0)k\beta^k t^{(k-1)}}{(\beta^k + t^k)^2}$	$\frac{(\alpha - BW_0)t^{k-1}}{(\beta^k + t^k)}$
6	Richards	$BW_t = \frac{\alpha}{(1 + \beta \times e^{-kt})^{-\frac{1}{m}}}$	$\frac{\alpha k\beta e^{-kt}}{(-m)(1 + \beta e^{-kt})^{(1+\frac{1}{-m})}}$	$\frac{\frac{\alpha}{(1+\beta e^{-kt})^{1/-m}} - \frac{\alpha}{(1+\beta)^{1/-m}}}{t}$

Note: BWt—body weight (g) at time t; BW_0 - initial body weight (g); α - upper asymptotic body weight (g); t - age (weeks); β, k, and m - parameters specific for the function; β - characterizes the first part of growth before the point of inflection; k describes the second part in which the growth rate decreases until the animal reaches the upper asymptotic body weight or mature body weight (α), m is the shape parameter determining the position of the curve point, e – the Euler's number (~ 2.718282).

group) or Richards function (treatment group) (**Table 3**). Average weekly gain (AWGt) was computed as AWGt = (BWt – BW0)/t (**Table 3**). The maximum AWGt value (AWGmax) was determined as its value when AWGt = WGt (Nguyen Xuan Trach, 2023). The most appropriate slaughter age was defined as the week at which AWGt reached its maximum (AWGmax), aligning with the principle of diminishing returns (Drummond & Goodwin, 2004; Nguyen Xuan Trach, 2023). When the AWGt reached its maximum was noted as the most technically appropriate slaughter age (Bo *et al.*, 2023; 2025).

The economically optimal slaughter age was determined based on profit maximization, when the marginal value output (MVOt) equaled the marginal input cost (MICt) (Nguyen Xuan Trach, 2023). MVOt was calculated by multiplying the current market price of body weight (100,000; 115,000; and 120,000 VND kg^{-1}) by the weekly weight gain. MICt included all additional weekly rearing costs (feed, labor, veterinary care, housing, and consumables).

Results

Parameters of the growth curves

The estimated parameters in the growth curves of Tien Yen females raised by the two diets were different even though these chickens were described using the same model (**Table 4**). The upper asymptotic body weight (α) shows the maturity of the animals and the α value reaches its maximum when the chickens are mature. In this study, the α values for the control group were lower than for the treatment group in all the models. These α values for Tien Yen females raised in the control group were estimated to be from 1,650.20g (Janoschek) to 1,762.14g (von Bertalanffy) and these values for Tien Yen females raised in the treatment group were from 1,798.49g (Richards) to 1,970.95g (von Bertalanffy). The α values were the highest in the

Table 4. Different estimated parameters in growth curve models of Tien Yen female chicken

Functions	Treatments	α (g)	β	k	m	BW_0 (g)
von Bertalanffy	Control	1762.14 ± 8.47	1.06 ± 0.02	0.186 ± 0.003	-	-
	CT1	1970.95 ± 12.02	1.00 ± 0.02	0.163 ± 0.003	-	-
Janoschek	Control	1650.20 ± 4.22	-	0.002 ± 0.0002	2.55 ± 0.04	129.44 ± 8.08
	CT1	1802.88 ± 5.84	-	0.002 ± 0.0002	2.50 ± 0.05	132.81 ± 9.30
Gompertz	Control	1728.29 ± 6.70	4.97 ± 0.13	0.223 ± 0.003	-	-
	CT1	1916.29 ± 9.22	4.75 ± 0.12	0.200 ± 0.003	-	-
Logistic	Control	1674.02 ± 4.39	-	0.338 ± 0.004	-	73.64 ± 2.82
	CT1	1833.47 ± 5.79	-	0.313 ± 0.004	-	82.03±3.26
Lopez	Control	1737.31 ± 8.55	9.72 ± 0.06	3.61 ± 0.08	-	159.55±8.31
	CT1	1937.87 ± 12.66	10.49 ± 0.07	3.355 ± 0.08	-	157.94±9.48
Richards	Control	1728.28 ± 7.23	0.001 ± 0.06	0.223 ± 0.004	-0.0002 ± 0.011	-
	CT1	1798.49 ± 5.99	249.13 ± 84.37	0.436 ± 0.019	-2.074 ± 0.157	-

Note: BW0 - initial body weight (g); α— upper asymptotic body weight (g); t—age (weeks); β, k, and m—parameters specific for the function; β characterizes the first part of growth before the point of inflection; k describes the second part in which the growth rate decreases until the animal reaches the upper asymptotic body weight or mature body weight (α), m is the shape parameter determining the position of the curve point inflection.

von Bertalanffy model and lowest in the Logistic model for both groups.

The estimated mature growth rate (k) describes the second part of the growth rate, and it decreases until the animal reaches its mature body weight. In Tien Yen female chickens, the k values herein of the control group in the von Bertalanffy, Gompertz, Logistic, Lopez, and Richards models were higher than those of the treatment group. The k values of the Lopez model were the highest in both groups, and the k values in the Janoschek model were the lowest in both groups.

The best model for describing the growth curve of Tien Yen female chickens

The results indicated that the coefficient determination (R^2) values from all six models were higher than 95% (**Table 5**), so Tien Yen female chicken growth can be estimated by using any of the tested models. To choose the correct and best model, the values of BIC and AIC were ranked (**Table 5**). The Janoschek function was the best model that described the growth rate of Tien Yen females in the control group with the highest coefficient of determination (R^2 = 97.16 %), and the lowest AIC and BIC values (AIC = 17,277.80 and BIC = 17,304.30) (Table 5). On the other hand, the Richards model was the best function for describing the growth curve of female Tien Yen chickens in the treatment group, as this model had the highest R^2, and the lowest AIC and BIC values among the six models (R^2 = 96.94, AIC = 17,666.70, and BIC = 17,693.10) (**Table 5**).

Additionally, the von Bertalanffy function was the worst model to describe the growth rates of female Tien Yen chickens as it had the lowest coefficient of determination, and the highest AIC and BIC values in both groups (**Table 5**).

Prediction of body weight, weekly gain, average weekly gain, and suitable slaughter age

Based on the Janoschek model with the estimated parameters in **Table 4**, the predicted functions for body weight (BWt), weekly gain (WGt), and average weekly gain (AWGt) of Tien Yen female chickens according to weeks of age (t) for the control group were computed as follows:

Table 5. Coefficient of determination, correlation, Akaike information criterion, and Bayesian information criterion values in the six models to estimate the growth of Tien Yen female chickens

Function	Treatment	Model ranking with			AIC	BIC	R^2 (%)
		AIC	BIC	R^2 (%)			
von Bertalanffy	Control	6	6	6	17784.0	17805.2	95.99
	CT1	6	6	6	18103.4	18124.5	95.87
Janoschek	Control	1	1	1	17277.8	17304.3	97.16
	CT1	3	3	3	17732.6	17759.1	96.80
Gompertz	Control	4	4	4	17602.8	17624	96.46
	CT1	5	5	5	17954.3	17975.5	96.27
Logistic	Control	2	2	2	17288.9	17310.1	97.14
	CT1	2	2	2	17716.5	17737.6	96.83
Lopez	Control	3	3	3	17571.5	17597.9	96.54
	CT1	4	4	4	17940.0	17966.4	96.31
Richards	Control	5	5	4	17604.70	17631.20	96.46
	CT1	1	1	1	17666.7	17693.1	96.94

Note: AIC: Akaike information criterion,

BIC: Bayesian information criterion,

Cor: Pearson's correlation between the predicted and actual body weights,

R^2: Coefficient of determination

Body weights (BW_t) = $1650.20 - (1650.20 - 129.44)e^{-0.002t^{2.55}}$;

Weekly gain (WG_t) = $(1650.20 - 129.44) * (-0.002) * 2.55t^{(1.55)}e^{-0.002t^{2.55}}$; and

Average weekly gain (AWG_t) = $\frac{(1650.20-129.44)(1-e^{-0.002t^{2.55}})}{t}$.

Based on the Richards model, the respective prediction functions for the treatment group were calculated as follows:

Body weights (BW_t) = $\frac{1798.49}{(1+249.13e^{-0.436t})^{\frac{1}{2.074}}}$;

Weekly gain (WG_t) = $\frac{1798.49*0.436*249.13e^{2.074t}}{(2.074)(1+249.13e^{-0.436t})^{(1+\frac{1}{2.074})}}$; and

Average weekly gain (AWG_t) = $\frac{\frac{1798.49}{(1+249.13e^{-0.436t})^{1/2.074}}-\frac{1798.49}{(1+249.13)^{1/2.074}}}{t}$.

The measured and predicted values of BW, WG, and AWG of the chickens at different weeks of age are presented in **Table 6**. The BWs of female Tien Yen chickens increased steadily during the research period. At 24 weeks of age, the BWs of female Tien Yen chickens were 1,626.11g and 1,788.33g for the control group and treatment group, respectively. The weekly gains reached maximums at 10 and 11 weeks of age for the treatment group and control group, respectively (**Table 6**). The maximum average weekly gains, when WGt = AWGt, were obtained at 13.39 and 14.62 weeks of age for the control group and treatment group, respectively, and these were the best times for them to go to the slaughterhouse providing the highest technical efficiency. At these suitable slaughter times, the estimated weights for

Table 6. The actual body weight (BW_{real}, Mean ± SD) and predicted body weight (BW), weekly gain (WG), and average weekly gain (AWG) values of Tien Yen female chickens in the Janoschek model for the control group and the Richards model for treatment group

Week	Measured value of control group			Measured value of treatment group			Janoschek (control group)			Richards (treatment group)		
	BW_{real}	WG_{real}	AWG_{real}	BW_{real}	WG_{real}	AWG_{real}	BW_{jan}	WG_{jan}	AWG_{jan}	BW_{ric}	WG_{ric}	AWG_{ric}
0	30.30 ± 1.09	-	-	30.30 ± 1.09	-	-	129.44	-	-	125.41	-	-
1	71.12 ± 0.92	40.82	40.82	71.12 ± 0.92	40.82	40.82	132.84	8.63	3.39	154.60	32.31	29.19
2	140.80 ± 12.93	69.68	55.25	140.80 ± 12.93	69.68	55.25	149.15	24.92	9.85	190.47	39.67	32.53
3	226.37 ± 12.06	85.57	65.36	226.37 ± 12.06	85.57	65.36	184.11	45.54	18.22	234.46	48.58	36.35
4	315.33 ± 25.56	88.96	71.26	315.33 ± 25.56	88.96	71.26	240.93	68.27	27.87	288.22	59.25	40.70
5	404.67 ± 54.50	89.33	74.87	404.67 ± 54.50	89.34	74.87	320.63	90.93	38.24	353.59	71.80	45.64
6	478.67 ± 60.33	74.00	74.73	478.67 ± 60.33	74.00	74.73	422.04	111.33	48.77	432.45	86.20	51.17
7	538.67 ± 61.24	60.00	72.62	538.67 ± 61.24	60.00	72.62	541.88	127.49	58.92	526.48	102.04	57.30
8	659.33 ± 61.95	120.67	78.63	659.33 ± 61.95	120.66	78.63	675.09	137.87	68.21	636.69	118.34	63.91
9	802.00 ± 65.81	142.67	85.74	802.00 ± 65.81	142.67	85.74	815.39	141.60	76.22	762.73	133.31	70.81
10	932.00 ± 54.45	130.00	90.17	932.00 ± 54.45	130.00	90.17	956.02	138.56	82.66	902.00	144.33	77.66
11	1091.33 ± 51.04	159.33	96.46	1091.33 ± 51.04	159.33	96.46	1090.48	129.45	87.37	1049.08	148.46	83.97
12	1146.67 ± 60.70	55.33	93.03	1146.67 ± 60.70	55.34	93.03	1213.32	115.58	90.32	1195.88	143.57	89.21
13	1269.67 ± 36.82	123.00	95.34	1280.22 ± 90.74	133.55	96.15	1320.63	98.67	91.63	1333.18	129.65	92.91
14	1397.56 ± 44.55	127.89	97.66	1427.89 ± 88.26	147.67	99.83	1410.26	80.55	91.49	1453.00	109.22	94.83
15	1506.11 ± 55.50	108.56	98.39	1556.11 ± 99.39	128.22	101.72	1481.88	62.87	90.16	1550.78	86.27	95.02
16	1578.33 ± 72.69	72.22	96.75	1650.33 ± 96.61	94.22	101.25	1536.57	46.89	87.95	1625.96	64.52	93.78
17	1625.00 ± 114.18	46.67	93.81	1716.89 ± 116.59	66.56	99.21	1576.49	33.40	85.12	1680.99	46.21	91.50
18	1644.67 ± 129.71	19.67	89.69	1754.56 ± 102.43	37.67	95.79	1604.31	22.71	81.94	1719.77	32.05	88.58
19	1650.33 ± 86.80	5.67	85.27	1769.00 ± 86.15	14.44	91.51	1622.82	14.73	78.60	1746.37	21.72	85.31
20	1641.67 ± 64.59	-8.67	80.57	1766.56 ± 109.89	-2.44	86.81	1634.57	9.11	75.26	1764.26	14.49	81.94
21	1607.33 ± 47.94	-34.33	75.10	1743.11 ± 124.81	-23.45	81.56	1641.67	5.36	72.01	1776.12	9.57	78.61
22	1614.89 ± 69.03	7.56	72.03	1760.67 ± 111.92	17.56	78.65	1645.75	3.00	68.92	1783.93	6.27	75.39
23	1621.78 ± 118.59	6.89	69.19	1777.00 ± 105.78	16.33	75.94	1647.99	1.60	66.02	1789.03	4.09	72.33
24	1626.11 ± 112.50	4.33	66.49	1788.33 ± 110.36	11.33	73.25	1649.15	0.81	63.32	1792.36	2.66	69.46

Note: Mean: average body weight (g); SD: Standard deviation; BW: Body weight (g); WG: Weekly gain (g $week^{-1}$); AWG: Average weekly gain (g $week^{-1}$).

female Tien Yen chickens in the control group and treatment group were 1,357.33g and 1,516.34g, respectively.

The estimated results of the marginal value output (MVO) based on the current prices of 100,000 VND kg^{-1}, 115,000 VND kg^{-1}, and 120,000 VND kg^{-1} body weight and the actual marginal input cost (MIC) for female Tien Yen chickens in the control group and treatment group are presented in **Table 7**.

The point when MVO = MIC indicated the suitable slaughter age for the highest economic efficiency. When the price was 100,000 VND kg^{-1}, the estimated slaughter ages for female Tien Yen chickens in the control group and treatment group were 13.75 weeks (1,342.40g) and 14.71 weeks (1,524.57g), respectively. When the price was 115,000 VND kg^{-1}, the estimated slaughter ages for female Tien Yen chickens in the control group and treatment group were 14.33 weeks (1,392.89g) and 15.17 weeks (1,565.23g), respectively. When the price was 120,000 VND kg^{-1}, the estimated slaughter ages for female Tien Yen chickens in the control group and treatment group were 14.50 weeks (1,1406.29g) and 15.31 weeks (1,576.09g), respectively.

Discussion

This study indicated that any of the six tested growth models could be used for modeling the

Table 7. Marginal value output (MVO) and marginal input cost (MIC) values for Tien Yen female chickens (VND/chicken/week)

Weeks	Control group				CT1			
	MVO100	MVO115	MVO120	MIC	MVO100	MVO115	MVO120	MIC
1	774.04	890.14	928.85	4048.00	3231.76	3716.53	3878.12	4186.00
2	2244.61	2581.30	2693.53	4446.00	3967.99	4563.19	4761.59	4559.00
3	4119.69	4737.64	4943.63	4844.00	4858.84	5587.67	5830.61	4932.00
4	6209.18	7140.55	7451.01	5242.00	5925.23	6814.01	7110.27	5305.00
5	8325.49	9574.32	9990.59	5640.00	7180.51	8257.59	8616.61	5678.00
6	10280.00	11822.00	12336.00	6038.00	8619.90	9912.88	10343.87	6051.00
7	11896.54	13681.02	14275.85	6436.00	10203.36	11733.87	12244.03	6424.00
8	13030.50	14985.08	15636.60	6834.00	11832.52	13607.40	14199.02	6797.00
9	13587.20	15625.28	16304.64	7232.00	13328.44	15327.71	15994.13	7170.00
10	13534.55	15564.73	16241.46	7630.00	14430.11	16594.62	17316.13	7543.00
11	12906.66	14842.66	15487.99	8028.00	14843.47	17069.99	17812.16	7916.00
12	11796.77	13566.28	14156.12	8426.00	14355.23	16508.52	17226.28	8289.00
13	10340.87	11892.00	12409.05	8824.00	12963.79	14908.35	15556.54	8662.00
14	8695.33	9999.63	10434.39	9222.00	10921.14	12559.31	13105.37	9035.00
15	7013.19	8065.17	8415.83	9620.00	8627.07	9921.14	10352.49	9408.00
16	5424.06	6237.66	6508.87	10018.00	6452.24	7420.08	7742.69	9781.00
17	4020.91	4624.05	4825.10	10416.00	4621.65	5314.90	5545.98	10154.00
18	2855.51	3283.84	3426.62	10814.00	3205.56	3686.39	3846.67	10527.00
19	1941.48	2232.71	2329.78	11212.00	2172.92	2498.86	2607.50	10900.00
20	1262.93	1452.37	1515.51	11610.00	1449.76	1667.23	1739.72	11273.00
21	785.43	903.24	942.51	12008.00	956.97	1100.52	1148.36	11646.00
22	466.64	536.64	559.97	12406.00	627.20	721.27	752.63	12019.00
23	264.66	304.35	317.59	12804.00	409.13	470.50	490.96	12392.00
24	143.17	164.64	171.80	13202.00	266.07	305.98	319.28	12765.00

growth curves of Tien Yen females in the control and treatment groups. However, this study showed that Janoschek for the control group and Richards for the treatment group were the best models to estimate growth as they had the highest R^2 values (R^2 = 97.16, and 96.94%), and the lowest AIC and BIC values compared to the other models (**Table 5**). This finding was consistent with previous studies that demonstrated that the Richards model was the most appropriate for modeling chicken growth (Darmani *et al.*, 2010; Osei-Amponsah *et al.*, 2014; Michalczuk *et al.*, 2016; Kaplan & Gürcan, 2018; Vrána *et al.*, 2019).

The upper asymptotic body weights (α) of the Janoschek and Richards functions in female Tien Yen chickens in the control and treatment groups were lower than the values reported in Ri chickens in Vietnam (Moula *et al.,* 2011; Bo *et al.,* 2022), Mia chickens in Vietnam (Nguyen Hoang *et al.,* 2021; Tuan *et al.,* 2022), Creole chickens (Mata-Estrada *et al.,* 2020), Italian local chickens (Rizzi *et al.,* 2013), and Castellana Negra chickens (Miguel *et al.*, 2008). The growth curves of Ri chickens were modeled, and the α value of the Gompertz model reached 1,670g for females (Bo *et al.*, 2020). In addition, the α values of the Janoschek in the current study were lower than the 1,714.2g for females reported for Ri chickens raised in household conditions in Vietnam (Moula *et al.,* 2011). The α values in the current study were also lower than the 1,915.75g value for female Mia chickens raised in Vietnam (Nguyen Hoang *et al.,* 2021). However, the α values of the Janoschek and Richards functions in female Tien Yen chickens in the control and treatment groups were higher than the 1,322g value for females raised in Ghana (Osei-Amponsah *et al.,* 2014).

This study indicated that we can use any of the six tested models to describe the growth of female Tien Yen chickens raised by different diets because the coefficients of determination (R^2) were high in all six models herein (R^2 > 95%). The coefficients of determination (R^2) of all six models herein were lower than those in studies by Bo *et al.* (2022) (R^2 = 96.79 to 98.74) and Yang *et al.* (2006) (R^2 = 99.52 to 99.91%). However, the coefficients of determination (R^2) in the current study were higher than those in a study by Osei-Amponsah *et al.* (2014) (R^2 = 86.6 to 96.7%).

The growth rate factors (maturation rate k) observed with the Janoschek and Richards functions for the female Tien Yen chickens in this study were different between the control group and treatment group. These estimated k values of the control group were higher than those of treatment group in all models, except those values estimated by the Janoschek and Richards model. The growth rate factors in this study were estimated to be higher than the values investigated for other chicken breeds (Yang *et al.,* 2006; Moula *et al.,* 2011; Manjula *et al.,* 2018; Nguyen Hoang *et al.,* 2021; Bo *et al.,* 2022). In the study of Bo *et al.* (2022), the growth rate of Ri chickens was 0.17 g/week for females. The value reported in Mia chickens was 0.13 g week^{-1} for both males and females (Nguyen Hoang *et al.,* 2021). The k value of Chinese Yellow chickens was 0.14 g week^{-1} for females (Yang *et al.,* 2006). The k value of Ri chickens was 0.129 g week^{-1} for females (Moula *et al.,* 2011). In another study, this value of Korean native chickens was 0.102 g week^{-1} (Manjula *et al.,* 2018).

The ages and body weights of Tien Yen female chickens in the control group and treatment group were like the values found in other local chicken breeds raised in Vietnam (Moula *et al.,* 2011; Nguyen Hoang *et al.,* 2021; Bo *et al.,* 2022). However, the values in this study were higher than those studied in Shaobo, Huaixiang, and Youxi chickens raised in China (Zhao *et al.,* 2015).

The suitable slaughter ages and weights of Tien Yen females were similar to the values obtained for Mia chickens (Hoang Anh Tuan *et al.,* 2022). The most suitable slaughter age of Mia chickens was 14 to 15 weeks for females based on the Lopez model. In another study, the suitable slaughter age of Mong chickens was 24 weeks with the body weight of 2,438g (Ngo Thi Thu Hien *et al.,* 2021).

Tien Yen is a native Vietnamese chicken breed. It is well-regarded in the market and by consumers, although it is characterized by relatively long rearing periods. Typically, roosters are raised for 8 to 9 months before slaughter, while hens are slaughtered at around 5 to 6 months of age (Hoang Xuan Truong, 2012). Vu Quynh Huong *et al.* (2023) evaluated three different slaughter ages (5, 5.5, and 6 months) to determine the optimal time for slaughtering Tien Yen hens. Their findings indicated that slaughtering at 5 months of age was the most effective in reducing lipid and cholesterol levels compared to the later time points.

Conclusions

The growth patterns of female Tien Yen chickens can be described using any of the following nonlinear models: von Bertalanffy, Janoschek, Gompertz, Logistic, Lopez, or Richards. Among these, the Janoschek model provided the best fit for Tien Yen chickens fed a diet lower in protein and fiber (control group) with the following derived prediction functions: Body weights (BW_t) = 1650.20 - (1650.20 – 129.44)$e^{-0.002t^{2.55}}$; Weekly gain (WG_t) = $(1650.20 - 129.44) * (-0.002) * 2.55t^{(1.55)}e^{-0.002t^{2.55}}$; and Average weekly gain (AWG_t) = $\frac{(1650.20-129.44)(1-e^{-0.002t^{2.55}})}{t}$, whereas the Richards model was most appropriate for the chickens fed a diet higher in protein and fiber (treatment group) with the following derived prediction functions: Body weights (BWt) $= \frac{1798.49}{(1+249.13e^{-0.436t})^{\frac{1}{2.074}}}$; Weekly gain ($WG_t$) = $\frac{1798.49*0.436*249.13e^{2.074t}}{(2.074)(1+249.13e^{-0.436t})^{(1+\frac{1}{2.074})}}$; and Average weekly gain (AWG_t) = $\frac{\frac{1798.49}{(1+249.13e^{-0.436t})^{1/2.074}}-\frac{1798.49}{(1+249.13)^{1/2.074}}}{t}$. The maximum AWG_t were therefore obtained at 13.39 and 14.62 weeks of age for the control group and treatment group, respectively. Under the current local market conditions, the estimated economically optimal slaughter ages were 14.33 weeks (1,392.89g) for the control group and 15.17 weeks (1,565.23g) for the treatment group.

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