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Research Article

The Evaluation for Recent Growth Performance of Bali Cattle using Non-linear Models

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Abstract: Growth curve modeling is essential for understanding livestock development, productivity, and efficiency. This study evaluated the growth patterns of Bali cattle, a resilient and economically significant breed in Indonesia, using five non-linear growth models: Brody, Gompertz, Logistic, Von Bertalanffy, and Modified Von Bertalanffy. Body weight data were collected from 256 males and 279 females at key growth stages from birth to 730 days. Goodness-of-fit criteria including Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), coefficient of determination (R^2), and correlation coefficient (r) were applied to identify the most suitable model for describing growth curves. The Gompertz model exhibited the best fit for males, with the lowest AIC (29.76) and BIC (28.58) and highest R^2 (0.9913) and r (0.9956). For females, the Modified Von Bertalanffy model performed best, with superior goodness-of-fit metrics. Growth parameter analysis revealed that males achieved higher mature weights (A) and slower growth rates (K), whereas females exhibited faster growth rates but matured at smaller sizes. These findings indicate distinct growth dynamics between sexes, influenced by genetic and physiological factors. This research emphasizes the importance of selecting appropriate models to understand critical growth stages, optimize nutrition, and enhance management and breeding strategies. The results offering valuable insights for breeders, farmers, and policymakers aiming to bolster beef production.

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1. Introduction

One of the most important indicators to predict livestock development, production and efficiency is by using growth curve as the parameter. Mathematical models that illustrate the relationship between age and body weight are commonly used to describe growth curve (Bahreini et al., 2014; Regadas Filho, 2014; Filipe et al., 2018). Non-linear models are particularly suitable for analyzing growth curve patterns of livestock. They effectively demonstrate how sigmoidal pathways appear. Through accurately growth curve modeling, these methods offer important insights into crucial growth stages and performance (Zimmerman et al., 2001; Cantalapiedra-Hijar et al., 2018). This allows livestock producers to make decisions regarding nutrition, management, and breeding programs. Ultimately, optimizing these factors contribute to better production outcomes, increased productivity and efficiency.

Bali cattle is one of Indonesian indigenous cattles originated from Bali Island. This particular type of cattle was domesticated breed of wild Banteng (Kikkawa et al., 2003; Mohamad et al., 2012; Wijaya et al., 2023). Bali cattle is well-known for its adaptability, which thrived under tropical environmental conditions and can utilize low-quality feed efficiently. Their adaptability and economic significance make them a cornerstone of Indonesia's beef production, particularly in traditional and semi-intensive farming systems (Martojo et al., 2012; Firman and Nono, 2021). Additionally, Bali cattle hold considerable cultural value, further solidifying their importance in local communities (Lisson et al., 2010). Understanding their growth characteristics is crucial for improving productivity, guiding genetic selection, and enhancing resource management strategies to support sustainable livestock development.

Non-linear growth models were widely used to analyze and predict growth patterns of cattle due to their ability to capture the sigmoidal characteristic of animal growth. These models, such as Gompertz, Logistic, and Von Bertalanffy, provide a better representation of biological growth processes compared to linear models, as they account for acceleration and deceleration phases and inflection points of livestock growth (Nogales et al., 2017; Selvaggi et al., 2017; Júnior et al., 2022). By accurately estimating growth parameters, non-linear models help identify critical growth stages, assess feeding efficiency, estimate breeding program outcomes, and determine the optimal slaughtering time. Furthermore, non-linear models were favorable tools for genetic selection, allowing breeders to assess individual growth trajectories and select animals with superior growth potential (Weber et al., 2021; Benvenga et al., 2022; Araujo et al., 2023). Overall, non-linear models enhance decision in nutrition, breeding, and management, leading to improved productivity and profitability in cattle production system. The best-fit model can be implemented to attain more reliable estimated growth parameters which are essential for effective cattle management.

This study aims to compare the performance of five non-linear models Brody, Gompertz, Logistic, and Von Bertalanffy, by assessing the growth performance of Bali cattle. The findings will determine the model which would be appropriate to describe the growth pattern and provide meaningful biological interpretations of the growth parameters of Bali cattle. The results of this research are expected to contribute to improved management practices, sustainable productivity, and better decision-making for government-owned breeding center, farmers and stakeholders.

2. Material and Methods

2.1. Data collection

The body weight records of Bali Cattle were obtained from Bali cattle breeding center of Republic Indonesia, Denpasar. Data comprised of recorded body weight at birth (0 day), body weight at weaning (205 day), then body weight at 365, 550, and 730 days. A data set included 256 males and 279 females Bali cattle born between 2017 and 2021. Bali cattle growth stages at each age are presented in Figure 1 and Figure 2, respectively for male and female.

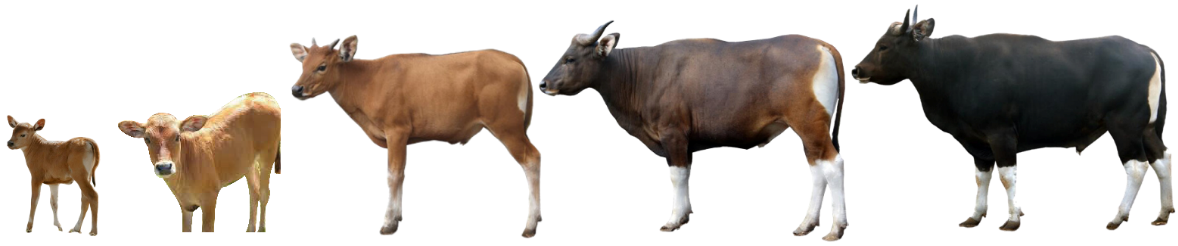

Figure 1. The illustration of male Bali cattle in each age stage.

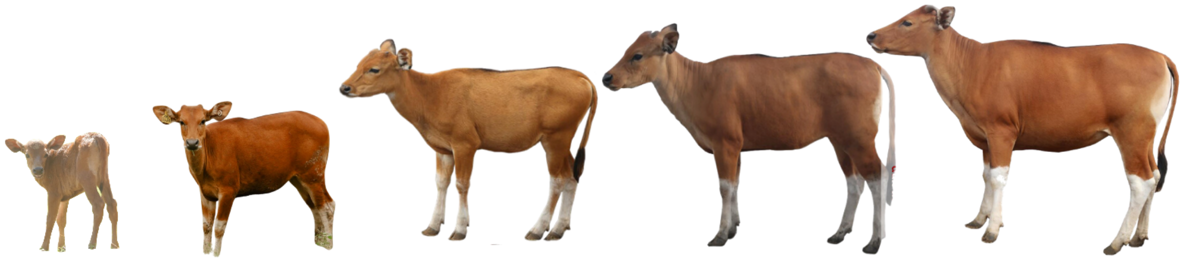

Figure 2. The illustration of female Bali cattle in each age stage.

2.2. Non-linear growth model

Individual body weight of Bali cattle was analyzed using five nonlinear growth curves: Gompertz, Logistic, Brody, Von Bertalanffy, and The modiffied Von Bertalanffy models. The NLIN procedure of Statistical Analysis System (SAS) OnDemand for Academics (SAS, 2021) was utilized to fit the observed body weights to these nonlinear models. The models used for predicting body weight is shown on Table 1.

Table 1. Mathematical equations of five growth models

Model	**Equations**	**Inflection Point**	
		Wi	***Ai***
Brody	$y = A(1 - Be- Kt)$	n/a	n/a
Gompertz	$y = Ae- Be- Kt$	$e^{-1}A$	*(ln B)/K*
Logistic	$y = A/(1 + Be- Kt)$	*A/2*	*(ln B)/K*
Von Bertalanfy	$y = A(1 - Be- Kt)^3$	*A(8/27)*	*(ln3B)/K*
Von Bertalanfy Modified	$y=A*(1- B*exp(-K*t))^2$	*8A/27*	*(ln3B)/K*

y, Body weight at t time; A, Asymptote body weights; B, Integral constant; e, Basic logarithm (2,71828); K, Average growth rate until adult age; Wi, Weight at inflection; Ai, Age of inflection; t, Time unit (week); n/a, not available.

2.3. Goodness of fit criteria

The appropriate model to describe the growth curve of Bali cattle was chosen using the goodness of fit criteria listed below. The Akaike Information Criterion (AIC) equation computed according to Narinc et al. (2014) as follows:

$$AIC = n\,ln\left(\frac{SSE}{n}\right) + 2p \quad (1)$$

The Bayesian Information Criterion (BIC) was computed using the equation Lewis et al. (2010) below:

$$BIC = n\,ln\left(\frac{SSE}{n}\right) + p\,ln\,(n) \quad (2)$$

Coefficient of determination (R^2) is used to evaluate the reliability of a model in linear regression analysis Equation provides the definition of this coefficient.

$$R^2 = 1 - \left(\frac{SSE}{SST}\right) \quad (3)$$

Where SSE is Error Sum of Square, SST is Total Sum of Square, n is the number of observations, ln indicates the natural logarithm, and p is the number of model parameters. The Pearson's correlation between prediction and observed body weight of Bali cattle chicken were estimated by using the CORR Procedure of SAS.

3. Results

The descriptive statistic of body weight for each age stage is presented in Table 2. Body weights of 205, 365, 550 and 730 days in female Bali cattle showed lower coefficients of variance than male Bali cattle. The estimated growth parameters for Bali cattle showed variation between males and females in all models. For males, the parameter A ranged from 410.17 kg (Logistic) to 542.64 kg (Modified Von Bertalanffy), with the Modified Von Bertalanffy model predicting the highest weight but slower growth rates (K = 0.002).

Table 2. The descriptive statistic of the body weight measured

Body weight	**Male**				**Female**			
(kg)	**Minimum**	**Maximum**	**Means**	**CV**	**Minimum**	**Maximum**	**Means**	**CV**
0 day	14	25	18.25	0.11	13	24	18.17	0.11
205 days	57	167	91.56	0.21	51	142	90.30	0.20
365 days	81	226	138.71	0.21	80	200	127.48	0.18
550 days	113	330	193.61	0.22	103	270	165.09	0.18
730 days	133	427	273.95	0.22	147	306	205.00	0.14

CV, coefficient of variation.

In females, the estimated growth parameters were ranging from 239.04 kg (Logistic) to 366.12 kg (Brody), with the Logistic model showed the fastest growth rate (K = 0.076). The Modified Von Bertalanffy model generally predicted higher A and slower K for both sexes. The detailed growth parameter for Bali cattle estimated by five models are presented in Table 3.

Table 3. Estimated growth parameters for Bali cattle using five non-linear models

Parameters	Brody	Gompertz	Logistic	Von Bertalanfy	Modified Von Bertalanfy
Male					
***A* [Coeff. ± SE]**	522.98±35.95	485.49±19.36	410.17±15.80	516.86±21.25	542.64±24.56
***B* [Coeff. ± SE]**	0.95±0.003	3.74±0.886	17.79±6.331	0.63±0.006	0.79±0.006
K	0.001	0.014	0.047	0.002	0.002
Wi	n/a	441.36	495.60	383.40	628.90
Ai	n/a	178.60	205.08	153.14	160.78
Female					
***A*[Coeff. ± SE]**	366.12±14.49	299.13±26.47	239.04±10.27	291.85±11.27	296.41±9.85
***B*[Coeff. ± SE]**	0.94±0.002	2.41±0.027	8.27±0.804	1.63±1.060	0.72±0.003
K	0.006	0.032	0.076	0.005	0.009
Wi	n/a	273.31	324.66	234.86	365.12
Ai	n/a	110.04	119.52	86.47	87.82

SE, Standard error; A, Asymptote body weights; *B*, Integral constant; *K*, Average growth rate until adult age; *Wi*, Weight at inflection; *Ai*, Age of inflection.

The goodness of fit for growth curve models in Bali cattle was evaluated using AIC, BIC, R^2, and correlation coefficient (r) values (Table 4). For males, the Gompertz model showed the best fit with the lowest AIC (29.76) and BIC (28.58), and the highest R^2 (0.9913) and r (0.9956), indicating excellent predictive accuracy. Similarly, Gompertz model also performed the best with the lowest AIC (26.59) and BIC (25.42), along with the highest R^2 (0.9937) and r (0.9969) for females. Other models, such as Logistic and Von Bertalanffy also showed strong fits, while the Gompertz model consistently provided the most accurate representation of growth for both male and female Bali cattle.

Table 4. Goodness of fit of growth curve models for body weights of Bali cattle

Model	Male				Female			
	AIC	BIC	R^2	r	AIC	BIC	R^2	r
Brody	246.68	35.06	0.8862	0.8862	26.71	25.64	0.9649	0.9820
Gompertz	29.76	28.58	0.9913	0.9956	26.59	25.42	0.9937	0.9969
Logistic	30.80	29.63	0.9923	0.9961	28.46	27.23	0.9920	0.9957
Von Bertalanffy	29.99	28.82	0.9904	0.9952	26.31	25.14	0.9935	0.9967
Modified Von Bertalanffy	30.92	29.72	0.9857	0.9927	26.25	25.03	0.9933	0.9966

AIC, Akaike Information Criterion; BIC, Bayesian Information Criterion, R^2, Coefficient of determination; r, Coefficient of correlation.

4. Discussion

The average body weights of male and female Bali cattle at birth (0 days) were similar, with males at 18.25 kg and females at 18.17 kg. By 730 days, males Bali cattle reached 273.95 kg, significantly heavier than females at 205.00 kg, indicating that males grow faster and reach maturity at earlier age. Compared to previous studies on Bali cattle, the body weight at 205 days was similar with Azis et al. (2023). The body weight of 730 days 273.95 kg for males and 205.00 kg for females were higher than the findings of Jakaria et al. (2019) at extensive rearing system (208.7 kg and 168.0 kg, respectively). Garantjang et al. (2020) reported body weight of Bali bull at the Village Breeding Center Bone South Sulawesi were 210.25 kg. Environmental factors such as feeding, housing conditions, and climatic stressors can significantly influence growth rates in cattle. These conditions may affect males and females differently, particularly in terms of metabolic demands, stress tolerance, and nutrient utilization. While this study did not specifically differentiate management strategies by sex, potential differences in how males and females respond to environmental factors could partially explain the observed growth variations. In comparison to other Indonesian breeds, the result of this study was lower than Madura cattle as reported by Prihandini et al. (2020) that body weight for male and female at 2 years were 306.66 and 282.76 kg respectively. The body weight of male Bali cattle at 2 year was higher than male Pasundan cattle (257.0 kg), whereas female Bali cattle were similar with female Pasundan cattle (204.5 kg) (Sumaryadi et al., 2021).

The estimated *A* parameter of Bali cattle showed that males consistently have higher mature weights than females across all models. The Brody and Modified Von Bertalanffy models predicted the highest *A* for males (522.98 kg and 542.64 kg, respectively), while the Logistic model provided the lowest estimate (410.17 kg). For females, the Brody model estimated the highest *A* (366.12 kg), whereas the Logistic model produced the lowest (239.04 kg). Compared to other breeds Bali cattle show lower *A* value. Adinata et al. (2022) reported higher *A* value of Ongole grade cattle ranged from 596.87 to 857.64 for male and ranged from 504.24 to 692.35 for female. The parameter *A* represented the maximum body weight cattle can achieve, reflecting its growth potential and genetic capacity (Grossi et al., 2008; Walmsley et al., 2016). production in tropical regions. Sex-based differences in mature body weight and growth potential are influenced by genetics and hormones. Males generally express more growth-related genes and produce higher levels of testosterone, which enhances muscle development and overall size. These factors, along with the influence of sex chromosomes, help explain why males have higher mature weights and slower, sustained growth compared to females (Kassahun et al., 2022).

The estimated of parameter *B* for Bali cattle varied across the five models. The Logistic model produced the highest value of *B* (17.79) and (8.27), respectively for male and female. The Von Bertalanffy model provided the lowest estimates (0.63) and (1.63) respectively. This result were similar to previous studies in Bahashwan et al. (2015) which reported the highest *B* values estimated by Logistic model and lowest *B* (0.52) estimated by Von Bertalanffy model in Dhofari cattle. Marinho et al. (2013) also reported lower *B* values in Nellore cattle (0.52) and (0.92) respectively, estimated by Von Bertalanffy and Brody models. These results suggested that Bali cattle exhibit a relatively faster early growth phase indicated by higher *B* values, which may contribute to their efficiency in reaching moderate mature weights. Differences between studies may be attributed to variations in genetic background, environmental conditions, and management practices. For example, Bali cattle raised under improved feeding and housing conditions tend to show enhanced growth compared to those in extensive systems, as seen in the studies by Jakaria et al. (2019) and Kurlyana et al. (2023). These comparisons highlight how the current results reflect a unique interaction of breed genetics with optimized management strategies, contributing to improved performance.

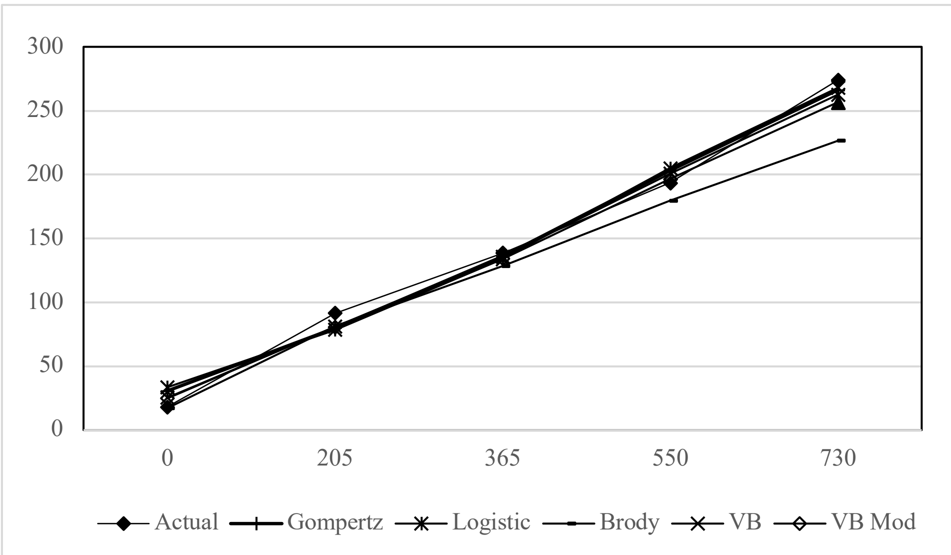

Figure 3. Actual and prediction of growth curve for male Bali cattle.

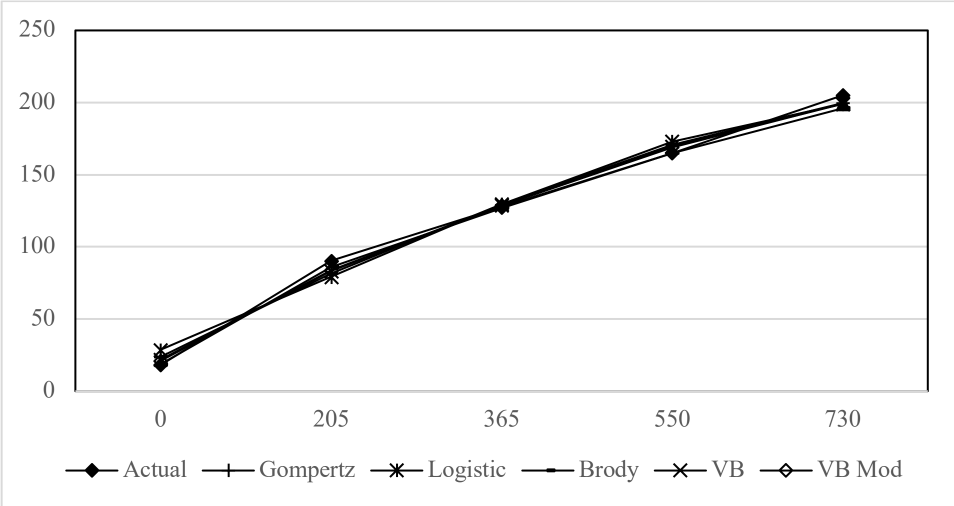

Figure 4. Actual and prediction of growth curve for female Bali cattle.

The growth rates (*K*) estimated for Bali cattle demonstrated significant variability across models. Logistic model showed the highest values and the Brody model showed the lowest, suggesting the differences in how these models captured early compared with sustained growth. Female cattle exhibited consistently higher *K* values than males across all models (Figure 3 and 4), aligning with findings in other breeds such as Nelore cattle (Forni et al.*,* 2009; Marinho et al.*,* 2013; Júnior et al.*,* 2022), and Angus cattle (Goldberg and Ravagnolo, 2015), where females often showed acceleration in early growth due to physiological maturity differences. Gompertz and Logistic models frequently provided higher *K* values than the Brody and Von Bertalanffy models. This result is similar with the studies on Zebu cattle (Domínguez-Viveros et al.*,* 2020). The higher *K* values estimated for the Logistic model emphasize rapid early growth which was crucial for efficient meat production, while the lower *K* estimated by Brody model reflected a focus on long-term growth sustainability. These results suggested that sex and growth models significantly influenced growth rate predictions, highlighting the need for tailored approaches in beef cattle management.

The estimated *Wi* and *Ai* for Bali cattle exhibited notable variations across models, reflecting differences in how these models capture dynamics of growth. The Modified Von Bertalanffy model predicted the highest *Wi* for both males (628.90 kg) and females (365.12 kg), while the Von Bertalanffy model estimates the lowest values, indicating a more conservative projection of Wi. The Logistic model estimates slightly higher *Wi* and *Ai* than the Gompertz model, suggesting a delayed, however rapid growth phase. The *Ai* values were consistently lower for females across all models, indicating earlier attainment of peak growth compared to males, similiar with Cano et al. (2016) findings. Gompertz and Logistic models showed higher *Wi* and *Ai* than Von Bertalanffy. The result was similar with previous studies by Domínguez-Viveros et al. (2020) on Zebu cattle, and Domínguez-Viveros et al (2023) on pure breed and crossbreed Limousin cattle. Bali cattle exhibited comparatively lower *Wi* due to their smaller frame size. These variations underscored the influence of breed characteristics and growth model selection on predicting growth patterns, essential for optimizing cattle production strategies.

The lowest values of AIC and BIC in Gompertz model indicated that this model was the best fit for males Bali cattle, whereas Modified Von Bertalanffy was the best fit model for females. The result was slightly different with the study growth model for Madura cattle by Hartati and Putra (2021) which reported the lowest AIC and BIC was in Von Bertalanffy model both for male and female. The correlation between prediction and observed body weight and R^2 were superior in all model except for Brody model, in both male and female. The result was in contrast to the estimated growth cruve for Nellore cattle which showed lower R^2 (89.16%) and (88.70%) respectively for Brody and Bertalanffy (Marinho et al.*,* 2013). Gompertz model was frequently reported to provide a superior fit for body weight growth for male Bali cattle due to its flexibility in capturing the sigmoidal growth pattern. On the other hand, Modified Von Bertalanffy model showed reasonable fit for female Bali cattle.

Conclusion

Bali cattle exhibited distinct growth characteristics between males and females, with males achieving higher mature weights (A) and slower growth rates (K), while females grew faster but matured at smaller sizes. The Gompertz model provided the best fit for males, while the Modified Von Bertalanffy model was most suitable for females, demonstrating that model performance varies with sex. These findings emphasize the importance of selecting sex-specific growth models to improve prediction accuracy and management strategies. Understanding these differences can help farmers and breeders optimize feeding regimes providing higher energy diets for males over a longer growth period to support their extended growth phase, while focusing on nutrient-rich early-life feeding for females to match their faster maturation. Strategically adjusting nutrition and management based on sex-specific growth patterns can improve feed efficiency, reduce production costs, and enhance the overall productivity and sustainability of Bali cattle farming in tropical environments.

Ethical Statement

The ethical approval from the committee of Animal Care and Welfare for this research was not necessary due to the used of secondary data only and there was no field experiment conducted.

Conflict of Interest

The authors declare that there were no conflicts of interest in any other financial institution nor organization regarding the material in this research.

Author Contributions

AS and PNG designed the study; PNG, DAL, NSP, MAM, FTK, and SVP performed the experiment; DAL, STP, AS, PNG and MAM analyzed and interpreted the data and prepared and wrote the manuscript; and AS and STP took part in critically checking the manuscript.

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