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Comparison of nonlinear models for predicting live weight growth curves in lamb production of Kıvırcık and Karacabey Merino

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Abstract: To achieve sustainable lamb production, it is crucial to determine the optimal slaughter age for maximum economic efficiency and have a comprehensive understanding of breed characteristics. This study focuses on evaluating different nonlinear models to determine the optimal slaughter age for Karacabey Merino and Kıvırcık lambs, renowned for their early development and superior meat quality, respectively. The dataset comprised age-related live weight data from 98 lambs, including 36 female and 15 male Kıvırcık lambs, as well as 33 female and 14 male Karacabey Merino lambs. Six models, namely, negative exponential, Brody, Gompertz, logistic, Bertalanffy, and Richards were utilized to analyze the data. The model parameters were estimated through an iterative process, and their goodness of fit was evaluated using various metrics. The adjusted coefficient of determination for male Kıvırcık lambs was 0.9755, while female Kıvırcık lambs exhibited a lower value of 0.8912. For Karacabey Merino lambs, males had an adjusted coefficient of determination of 0.9534, while females had a slightly lower value of 0.9044. The study concluded that the Brody model provided more accurate predictions for the growth curve of these sheep breeds compared to the other models.

Key words: Nonlinear models, growth curve, lamb, Kıvırcık, Karacabey Merino

1. Introduction

Lamb meat plays an important role in meeting the world's need for red meat, with its relevance extending beyond simple dietary requirements into larger realms of nutritional security and general public health. This high-quality protein source is abundant in essential amino acids, vitamins, and minerals and plays an important role in maintaining a balanced diet, increasing food security, and closing the red meat gap [1]. Given the growing worldwide population and the resulting increase in protein requirements, lamb meat, particularly from domestic breeds, offers a sustainable solution to this problem [2]. Furthermore, domestic sheep breeds can provide a stable and reliable supply of meat, paving the way for a future discussion of their roles in maintaining sustainable red meat production.

Considering the global importance of lamb meat, it is valuable to explore the local landscape of sheep breeds in Türkiye. The nation has a sizable population of domestic sheep, Merino crossbreeds, and exotic varieties of sheep. According to data from the Turkish Statistical Institute[1] (2023), among the 44.69 million sheep in Türkiye, 40.73 million belong to domestic breeds, while 3.96 million consist of Merino crosses and exotic breeds. Notably, sheep meat ranks as the second most consumed red meat in Türkiye, following beef, in line with prevailing conditions and consumer preferences.

Notably, the southern Marmara region stands out as a valuable hub for lamb meat production, owing to suitable pasturelands and climatic conditions. Exploiting this opportunity, the Kıvırcık and Karacabey Merino breeds, distinguished by their thin tail structure, are extensively employed in the region [3]. This distinctive feature provides adequate intermuscular and intramuscular lubrication, improving the overall quality of the produced meat.

Growth, defined as the continual alterations and development of an organism's tissues and organs over time, draws considerable interest from animal breeders who are

[1]Turkish Statistical Institute (2023). Data Portal for Statistics [online]. Website https://biruni.tuik.gov.tr/medas/?kn=101&locale=tr [accessed 10 April 2023].

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particularly focused on understanding both genetic and phenotypic associations across all stages of this process [4]. Growth curves, on the other hand, which plot animal weight against age, reveal growth trends, and the use of nonlinear models is particularly beneficial because it simplifies the collection of physiologically interpretable parameters from an enormous amount of data [5]. Furthermore, this process is becoming increasingly important, as these associations between parameters and animals' productive and reproductive characteristics serve as a valuable tool for implementing selection programs effectively [6]. The use of a growth curve allows for the prediction of various key features, such as an animal's weight at a specific age [7], optimal slaughter age [8], mature body weight [9], growth rate [5], and absence of infections [10] as well as the assessment of management elements influencing development, such as feed needs [7,11].

Several nonlinear models, including Brody, Gompertz, Janoschek, Logistic, Morgan-Mercer-Flodin, Negative Exponential, Richards, Verhulst, Von Bertalanffy, Weibull, monomolecular, quadratic, and cubic, have been extensively employed to forecast and analyze significant characteristics in diverse sheep breeds. These breeds include the Turkish Norduz [12], Hemşin [13], Morkaraman [14], Anatolian Merino [15], Iranian Mehraban [16], Baluchi [17] and Moghani [18], Harnai, [19] and Mengali [20] sheep breeds of Balochistan; Segureña [21], Santa Inês [6], Horro [22], Texel [17], Scottish Blackface [17], and West African Dwarf sheep [23] breeds. Furthermore, Brazilian Dorper crossbreeds with Morada Nova, Rabo Largo, and Santa Inês are also among the breeds that have been examined [9,24]. Overall, these studies demonstrate the significant influence of species, breed, handling methods, environmental conditions, and selective breeding on sheep growth curves, emphasizing the interconnected nature of these factors within this phenomenon.

The rate of growth in lamb production plays a role in determining both the quality meat yield and the ideal slaughter time. It is commonly acknowledged that various factors, including genetics, diet, and environmental circumstances, have significant impacts on lamb growth characteristics. Therefore, it is crucial for animal breeders to have an understanding of genetic and phenotypic correlations across developmental stages. A growth curve, which is developed from a nonlinear model, offers important information on animal weight, optimum slaughter age, mature body weight, growth rate, susceptibility to illness, and management needs. In addition, as was mentioned in the preceding paragraph, different breeds have different optimal models for predicting sheep growth. However, limited research exists on the Kıvırcık and Karacabey Merino breeds, highlighting the need for further investigation. Hence, the objective of this study was to unveil the growth curves and identify the optimal slaughter age of Kıvırcık and Karabey Merino lambs by employing various nonlinear models (namely, Negative Exponential (NEXP), Brody (BRO), Gompertz (GOM), Logistic (LOG), Bertalanffy (BER), and Richards (RIC)) that were housed within a single herd, ensuring uniformity, and were subjected to the same standard of care and feeding conditions.

2. Materials and methods

The age-related live weight (LW) data of the current study were derived from records of 98 Kıvırcık (36 females, 15 males) and Karacabey Merino (33 females, 14 males) lambs utilized in our previous research [25–28]. In order to ascertain the appropriate sample size for this study, pertinent literature and prior research in the field were consulted [29,30]. Female and male lambs were separated after the project's slaughtering procedure to prevent unwanted pregnancy. Furthermore, no lambs were sheared until they were one-year-old, which coincided with the completion of the study for growth monitoring purposes. In our earlier research, we also provided information regarding the feeding schedule and rearing conditions of lambs in great detail [31,32]. The same technician took the LW records of lambs at birth, weaning (3rd month), slaughter (5th month), and every month between 6–12 months of age. Lambs' birth weights were recorded within the first 12 h after birth, while all other weights were recorded before morning feeding (after at least 12 h of fasting) [33]. Scales with a sensitivity of 50 g were used to measure the weight of the lambs. The slaughter age was determined by considering the daily increase in LW between two consecutive measurements. A detailed description of the descriptive statistics regarding the LWs obtained at different intervals of time is provided in Table 1.

To model the age-related change in LW of Kıvırcık and Karacabey Merino female and male lambs, we used the five asymptotic nonlinear functions summarized in Table 2. Asymptotic models are those that describe indeterminate expansions and have limits that are asymptotically infinite according to the equation ($LW_{(t)=}LW_{\infty}$) [13].

Fits were made to each of the five nonlinear models to characterize the trend between mean LW and age. All analyses were performed with the "*minpack.lm*" package and plotted with the "*ggplot2*" package in R. Nonlinear fitting iterations were determined using the Levenberg–Marquardt algorithm [40]. The convergence criterion was 1.49×10^{-8} and the maxiter (positive integer) was set to 500. The following method was used to evaluate the relative merits of the models: First, the iterative process was used to determine values for the model parameters (*A*, *B*, and *k*), and second, residual standard error (RSE), degree of freedom (df), iteration number (IN), R-squared (R^2), adjusted R-squared ($adjR^2$), Akaike information criterion (AIC), and Bayesian

Table 1. Descriptive statistics of live weights measured in lambs over time[1].

Sex	Breed	Model	Age (months)									
			0	3	5	6	7	8	9	10	11	12
All	K	Mean	4.08	29.88	35.72	35.41	37.22	40.68	39.76	44.47	44.68	45.41
		SEM	0.09	0.48	0.67	0.70	0.61	0.73	0.71	0.92	0.79	0.84
		V	0.37	11.83	22.11	18.92	13.20	20.93	18.72	33.70	22.48	25.69
		CV	14.97	11.51	13.16	12.29	9.76	11.25	10.88	13.05	10.61	11.16
		Min	3.00	22.45	25.30	25.70	30.10	31.70	30.95	33.25	34.50	31.80
		Max	5.55	37.65	46.20	45.55	45.75	51.40	50.85	57.90	55.45	58.70
	KM	Mean	4.88	31.47	40.41	41.32	43.62	48.48	47.73	51.98	55.84	58.71
		SEM	0.11	0.56	0.76	0.79	0.88	0.94	0.87	0.99	1.19	1.00
		V	0.62	15.69	28.51	24.25	31.06	35.89	28.58	39.20	52.05	33.97
		CV	16.21	12.59	13.21	11.92	12.78	12.36	11.20	12.05	12.92	9.93
		Min	3.20	23.00	24.00	28.85	32.50	38.30	36.80	38.40	40.65	46.20
		Max	6.85	38.75	50.90	52.30	57.65	63.10	59.70	64.80	71.30	72.30
M	K	Mean	4.31	32.73	40.76	43.50	48.08	50.01	51.83	55.63	62.13	65.33
		SEM	0.18	0.39	0.81	1.42	1.13	0.97	0.73	0.32	0.10	0.66
		V	0.50	2.28	9.84	10.10	6.43	4.69	2.65	0.30	0.04	1.76
		CV	16.44	4.62	7.70	7.30	5.27	4.33	3.14	0.99	0.33	2.03
		Min	3.50	30.20	33.40	40.15	45.25	47.00	49.60	55.00	61.90	63.50
		Max	5.55	35.05	46.20	47.60	50.65	52.30	53.60	55.95	62.30	66.40
	KM	Mean	5.01	33.45	44.93	44.65	48.06	56.13	58.41	60.14	72.03	78.82
		SEM	0.16	0.87	0.85	0.08	0.56	2.11	2.89	1.34	1.99	2.61
		V	0.39	11.26	10.91	0.02	1.26	22.24	41.63	8.94	19.72	33.98
		CV	12.45	10.03	7.35	0.30	2.34	8.40	11.05	4.97	6.17	7.40
		Min	3.80	29.00	39.70	44.55	46.85	51.35	51.75	56.90	66.30	69.90
		Max	6.00	38.05	50.90	44.80	49.25	63.10	66.00	63.25	78.15	84.50
F	K	Mean	3.91	28.70	33.57	34.28	36.46	39.68	39.16	42.93	44.42	45.03
		SEM	0.08	0.55	0.58	0.56	0.58	0.61	0.61	0.72	0.77	0.78
		V	0.22	11.08	11.85	10.71	11.45	12.98	12.99	18.32	20.63	21.11
		CV	12.01	11.60	10.26	9.55	9.28	9.08	9.20	9.97	10.22	10.20
		Min	3.00	22.45	25.30	25.70	27.95	31.70	30.95	33.25	34.50	31.80
		Max	4.85	37.65	42.50	40.30	42.85	48.80	47.65	52.90	55.45	51.95
	KM	Mean	4.82	30.62	38.89	40.63	42.71	47.03	47.45	50.76	54.25	57.94
		SEM	0.14	0.67	0.73	0.81	0.87	0.85	0.75	0.85	0.74	0.89
		V	0.73	15.50	17.88	22.57	26.56	24.83	17.99	23.83	15.81	25.55
		CV	17.72	12.86	10.87	11.69	12.07	10.60	8.94	9.62	7.33	8.73
		Min	3.20	23.00	31.35	28.85	32.50	38.30	37.40	40.25	44.45	46.20
		Max	6.85	38.75	47.65	49.50	53.90	58.00	56.55	60.95	62.45	69.45

[1] Descriptive statistic was provided after the outliers were eliminated. M: Male; F: Female; K: Kıvırcık; KM: Karacabey Merino; SEM: Standard error of mean, V: Variance, CV: Coefficient of variance, Min.: Minimum, Max.: Maximum.

information criterion (BIC) were used to assess each model's goodness of fit, as indicated by the formulas provided below:

$$\mathrm{RSE} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-p-1}} \quad (1)$$

where y_i are the observed values, y_i are the predicted values, n is the number of observations, and p is the number of predictors.

$$\mathrm{df} = n - p - 1 \quad (2)$$

for regression models, the degrees of freedom for the residuals is $n - p - 1$ where n is the number of observations and p is the number of predictors.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \quad (3)$$

Table 2. Nonlinear models examined to describe age-related live weight in Kıvırcık and Karacabey Merino lambs.

Model	Formula	Inflection weight	Inflection age	Reference
NEXP	LW = *A* (1-exp(-*k*t))	NA	NA	Brown et al. [34]
BRO	LW = *A* (1-*B* exp(-*k*t))	NA	NA	Brody and Lardy [35]
GOM	LW = A exp(-*B* exp(-*k*t))	A/e	lnB/k	Laird [36]
LOG	LW = *A*/(1+*B* exp(-*k*t))	$A/2$	lnB/k	Nelder [37]
BER	LW = *A* (1-*B* exp(-*k*t))^3	$8/27\,A$	$ln3B/k$	Bertalanffy [38]
RIC	LW = *A* (1-*B* exp(-*k*t))$^{1/m}$	$A\,(1-(1/m))^m$	$\ln mB/k$	Richards [39]

NEXP: Negative exponential; BRO: Brody; GOM: Gompertz; LOG: Logistic; BER: Bertalanffy; RIC: Richards; LW: Live weight; NA: Nonavailable; : Weight at birth corresponding to t = 0; *A*: Weight at maturity; *B*: Constant of integration; *k*: Rate constant of logarithmic function of weight; *m*: Shape parameter; t: Age (months).

where $\bar{y}_i$ is the mean of the observed values.

$$adjR^2 = 1 - \frac{(1-R^2)-(n-1)}{n-p-1} \quad (4)$$

where n is the number of observations and p is the number of predictors.

$$AIC = -2\log(L) + 2k \quad (5)$$

where L is the maximum value of the likelihood function for the model and k is the number of parameters in the model.

$$BIC = -2\log(L) + klog(n) \quad (6)$$

where L is the maximum value of the likelihood function for the model, k is the number of parameters in the model, and n is the number of observations.

A model is considered to be well-fitted when the values of R^2 and $adiR^2$ approach 1, whereas lesser values of AIC and BIC indicate a superior fit. Furthermore, the inflection weight (IW) and inflection age (IA) for each model were determined using the methods suggested by Lupi et al. [24], with a detailed formula given in Table 1.

3. Results and discussion

Breeding and commercial goals determine whether animals are chosen for reduced or increased mature weight. It may be preferable to breed for early maturity and lower mature weight when the goal is to produce animals with fewer energy requirements [41]. If, on the other hand, meeting market demand for heavier adult animals is the goal, then delaying maturity becomes more important. In other words, when using the growth curve as a selection criterion, it is critical to find a point on the curve that corresponds to the commercial objectives, especially the target slaughter weight [42]. However, depending on the individual manufacturing method and customer preferences, this selection point may change. In the case of Kıvırcık and Karacabey Merino sheep, their development patterns remain poorly understood due to the paucity of studies employing nonlinear models. The lack of research using nonlinear models has hindered our ability to understand the growth dynamics in these sheep breeds. Therefore, more studies utilizing nonlinear models will be required to gain a comprehensive understanding of their development. By performing these studies, we will be able to uncover the intricate patterns of growth and identify the factors that influence growth, such as breed, sex, birth type, season, year of birth, and the age of the dam at lambing [43].

The RIC model employed in this study exhibited poor performance as it did not converge within the maximum number of iterations, resulting in nonbiologically acceptable values for *A*, IW, and IA. Additionally, the LOG model showed the second worst fitting on LW-age records for all lambs with the highest AIC, BIC and RSE and the lowest R^2 and adjR^2 among the tested models (Table 3). In contrast, BRO performed well in predicting the growth curves of both male and female Kıvırcık and Karacabey Merino lambs, as evidenced by the highest values of R^2 and adjR^2 and the lowest values of RSE, IN, AIC, and BIC. Furthermore, the outcomes of this study reflect the effectiveness of the BRO model in assessing the growth patterns of various sheep breeds, including Iranian Kordi [44], Baluchi [45], and Mehraban sheep [46], West African Dwarf sheep [23], Turkish Kıvırcık [47], Dağlıç [47], Hemşin [13], and Morkaraman sheep [48]. Nonetheless, the literature reveals studies where different models have proven effective, even within the same breed. For instance, Demir and Şahinler [49] reported that the Richards and LOG models displayed greater efficacy in assessing the growth patterns of Morkaraman breeds. Moreover, several studies have shown that fitting alternative growth functions to the same weight-age data generates varied parameter values for nonlinear models [23,50]. These results highlight the fact that the predicted parameter values are highly sensitive to the selection of the model.

The asymptotic weight of animals, denoted by parameter *A*, serves as an indicator of the possible mature weight they might acquire over time, and its value has been directly affected by both genetic and environmental factors [51]. In both the Kıvırcık and Karacabey Merino

Table 3. Estimated parameters describing the growth curve of lambs using nonlinear models[1].

Sex	Breed	Model	*A*	*B*	*k*	*m*	IW[2]	IA[2]	RSE	df	IN	R^2	adj^{R}2	AIC	BIC
All	K	NEXP	44.55		0.32		NA	NA	4.80	412	11	0.8654	0.8648	2477	2490
		BRO	45.36	0.90	0.28		NA	NA	4.53	411	11	0.8804	0.8795	2431	2447
		GOM	43.05	2.02	0.49		15.84	1.45	4.78	411	14	0.8666	0.8656	2476	2492
		LOG	41.86	5.29	0.75		NA	NA	5.06	411	19	0.8505	0.8494	2523	2539
		BER	43.63	0.51	0.41		12.93	1.01	4.69	411	13	0.8718	0.8708	2460	2476
		RIC	206.5	1.00	6.3×10^{-4}	3.23	NC	NC	4.35	410	99	0.8902	0.8891	2397	2418
	KM	NEXP	59.41		0.22		NA	NA	5.90	416	8	0.8670	0.8663	2675	2687
		BRO	62.46	0.91	0.18		NA	NA	5.57	415	9	0.8821	0.8812	2626	2642
		GOM	56.13	1.98	0.34		20.65	2.00	5.91	415	13	0.8670	0.8660	2677	2693
		LOG	54.15	4.52	0.49		NA	NA	6.28	415	14	0.8499	0.8488	2727	2743
		BER	57.41	0.50	0.29		17.01	1.44	5.78	415	11	0.8726	0.8717	2659	2675
		RIC	492.4	1.00	6.2×10^{-4}	2.27	NC	NC	5.37	414	99	0.8904	0.8893	2598	2618
M	K	NEXP	66.15		0.20		NA	NA	3.68	74	9	0.9619	0.9608	418	425
		BRO	70.19	0.93	0.16		NA	NA	2.91	73	8	0.9765	0.9755	383	392
		GOM	60.39	2.15	0.35		22.22	2.16	3.88	73	9	0.9583	0.9565	427	436
		LOG	57.58	5.41	0.54		NA	NA	4.75	73	13	0.9376	0.9350	457	467
		BER	62.27	0.53	0.29		18.45	1.62	3.55	73	9	0.9651	0.9637	413	422
		RIC	793.6	1.00	4.78×10^{-4}	2.03	NC	NC	2.33	72	99	0.9851	0.9842	351	362
	KM	NEXP	87.25		0.14		NA	NA	5.52	75	5	0.9399	0.9383	486	493
		BRO	100.63	0.94	0.10		NA	NA	4.79	74	3	0.9553	0.9534	465	474
		GOM	76.39	2.16	0.27		28.10	2.86	5.70	74	8	0.9369	0.9343	491	501
		LOG	71.31	5.37	0.42		NA	NA	6.50	74	12	0.9178	0.9144	512	521
		BER	80.16	0.54	0.21		23.75	2.30	5.39	74	11	0.9435	0.9412	483	492
		RIC	1132.0	1.00	9.00×10^{-4}	1.65	NC	NC	4.41	73	95	0.9626	0.9605	453	465
F	K	NEXP	44.96		0.28		NA	NA	4.18	346	11	0.8771	0.8764	1986	1998
		BRO	46.15	0.90	0.24		NA	NA	3.92	345	10	0.8922	0.8912	1943	1958
		GOM	43.45	1.92	0.41		15.98	1.60	4.23	345	15	0.8744	0.8733	1996	2011
		LOG	42.46	4.22	0.56		NA	NA	4.55	345	18	0.8546	0.8533	2047	2063
		BER	44.06	0.49	0.35		13.05	1.12	4.12	345	13	0.8810	0.8799	1977	1993
		RIC	258.6	1.00	5.26×10^{-4}	2.90	NC	NC	3.69	344	99	0.9046	0.9035	1902	1922
	KM	NEXP	59.62		0.20		NA	NA	5.04	331	9	0.8895	0.8888	2026	2037
		BRO	63.25	0.91	0.16		NA	NA	4.67	330	5	0.9053	0.9044	1976	1992
		GOM	56.39	1.94	0.31		20.75	2.13	5.05	330	13	0.8892	0.8882	2029	2044
		LOG	54.36	4.33	0.45		NA	NA	5.43	330	12	0.8720	0.8708	2077	2092
		BER	57.74	0.50	0.26		17.11	1.53	4.92	330	11	0.8951	0.8941	2010	2026
		RIC	447.2	1.00	8.82×10^{-4}	2.19	NC	NC	4.45	329	99	0.9141	0.9131	1946	1965

[1]Due to the Richards (RIC) model exceeding the maximum number of iterations, convergence was not attained.
[2]Inflection weight (IW) and inflection age (IA, months) parameters were not calculated for the RIC model due to the absence of convergence. M: Male; F: Female; K: Kıvırcık; KM: Karacabey Merino; NEXP: Negative exponential; BRO: Brody; GOM: Gompertz; LOG: Logistic; BER: Bertalanffy; NA: Nonavailable; NC: Not calculated; *A*: Weight at maturity; *B*: Constant of integration; *k*: Rate constant of logarithmic function of weight; *m*: Shape parameter; RSE: Residual standard error; df: Degree of freedom; IN: Iteration number; R^2: R-squared; adjR^2: Adjusted R-squared: AIC: Akaike information criterion; BIC: Bayesian information criterion.

breeds, the BRO model had the highest predictive value for the *A* parameter (45.36 and 62.46, respectively), while the LOG model had the lowest predictive value (41.86 and 54.15, respectively), as depicted in Table 3 and Figures 1.

Upon careful examination of Table 3, it becomes evident that sex plays a significant role in both breeds and exerts an influence on LW. The results indicate that the Pearson correlation coefficient between individual male and female

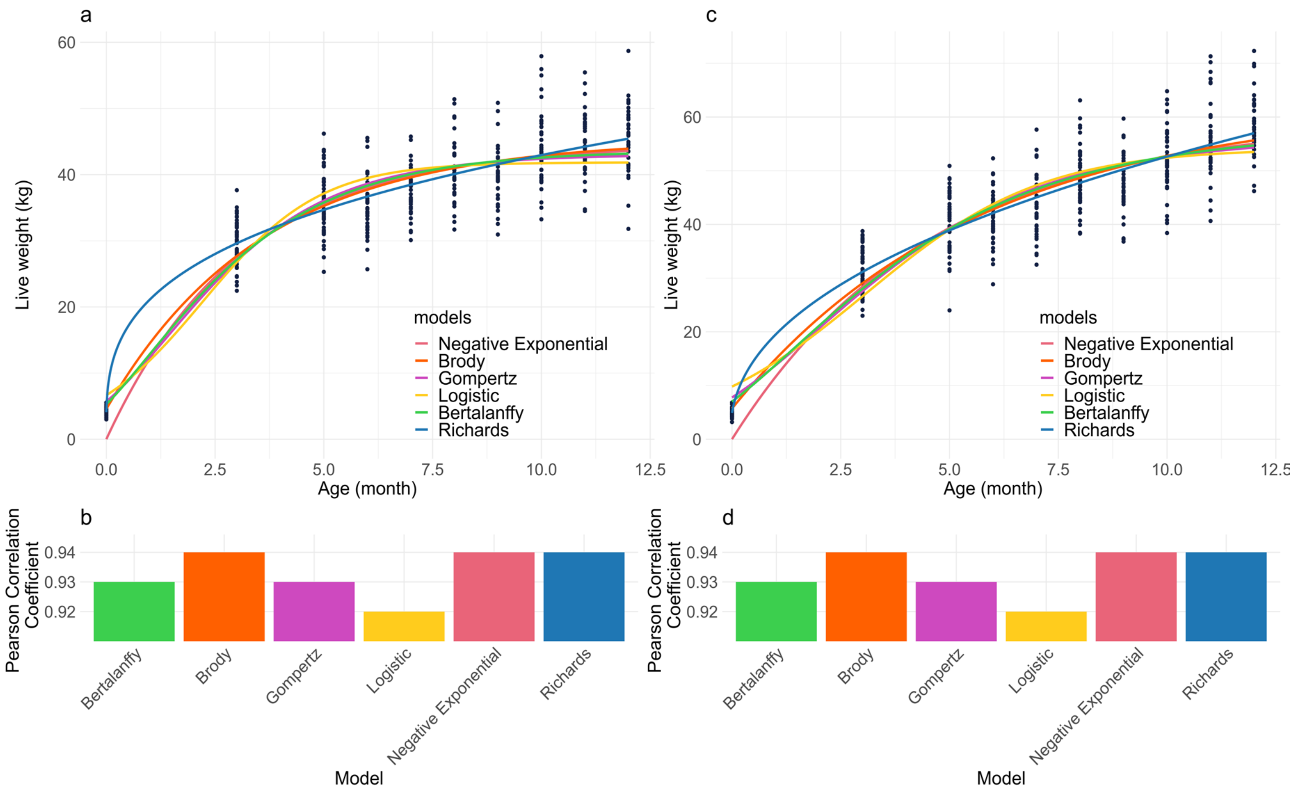

Figure 1. Growth curves of mixed sex Kıvırcık (a) and Karacabey Merino (c) lambs from birth to yearlings using different nonlinear models. Below each breed's growth curve (b, d), the Pearson correlation coefficient between the predicted and observed live weight values is given. Please note that Richards model did not achieve convergence and its inclusion on the figure is solely intended for informational purposes.

Kıvırcık and Karacabey lambs was found to be higher when compared to the correlation coefficients observed in mixed lambs. It would therefore be more accurate to use sex-specific growth curves for both breeds. The BRO model demonstrated superior performance in both Kıvırcık and Karacabey Merino lambs, regardless of sex, while the LOG model exhibited the poorest performance among the tested models, following the nonconverged RIC model. In both the Kıvırcık and Karacabey Merino breeds, the BRO model had the highest predictive value for the A parameter (70.19 and 100.63, respectively), while the LOG model had the lowest predictive value (57.58 and 71.31, respectively), as depicted in Table 3 and Figures 2 and 3. The observed and estimated outcomes of this study correspond to the published typical adult weight range for Kıvırcık and Karacabey Merino sheep as specified in the national inventory of native breeds [52]. According to the catalog, the typical mature weight of Kıvırcık males is between 60 and 70 kg, while females weigh between 45 and 55 kg. Additionally, the catalog states that adult male Karacabey Merino sheep weigh 80–100 kg, while adult females weigh 60–65 kg. Body weight differences between males and females can be linked to sexual dimorphism, which is regulated by testicular steroids and their metabolites. A previous study has shown that these hormonal variables affect male growth processes from prenatal development to maturity [53,54]. Furthermore, the high value of the *A* parameter observed in Karacabey Merino lambs suggests that this breed matures more slowly than the Kıvırcık breed, necessitating additional time aligning with the findings of Hojjati and Ghavi Hossein-Zadeh [16].

Parameter *B* in sheep, an integrated constant associated with early LW, holds limited biological importance; however, high *B* values of this parameter indicate low levels of maturity at birth [44,49]. In this study, male lambs of both Kıvırcık and Karacabey Merino breeds exhibited the highest *B* values when the LOG model was applied, with values of 5.41 and 5.37, respectively. In contrast, the lowest *B* values were observed in female lambs of both breeds when the BER model was utilized, yielding values of 0.49 and 0.50, respectively. The *B* value found in this study using the LOG model is higher than the values reported by Kopuzlu et al. [13] for Hemşin lambs (4.68) and by Lupi et al. [53] for Segurea sheep (4.06). It is, however, less than the values reported by Gbangboche et al. [23] for West African Dwarf sheep (10.48) and Latifi and Bohlouli [46] for Mehraban sheep (7.32).

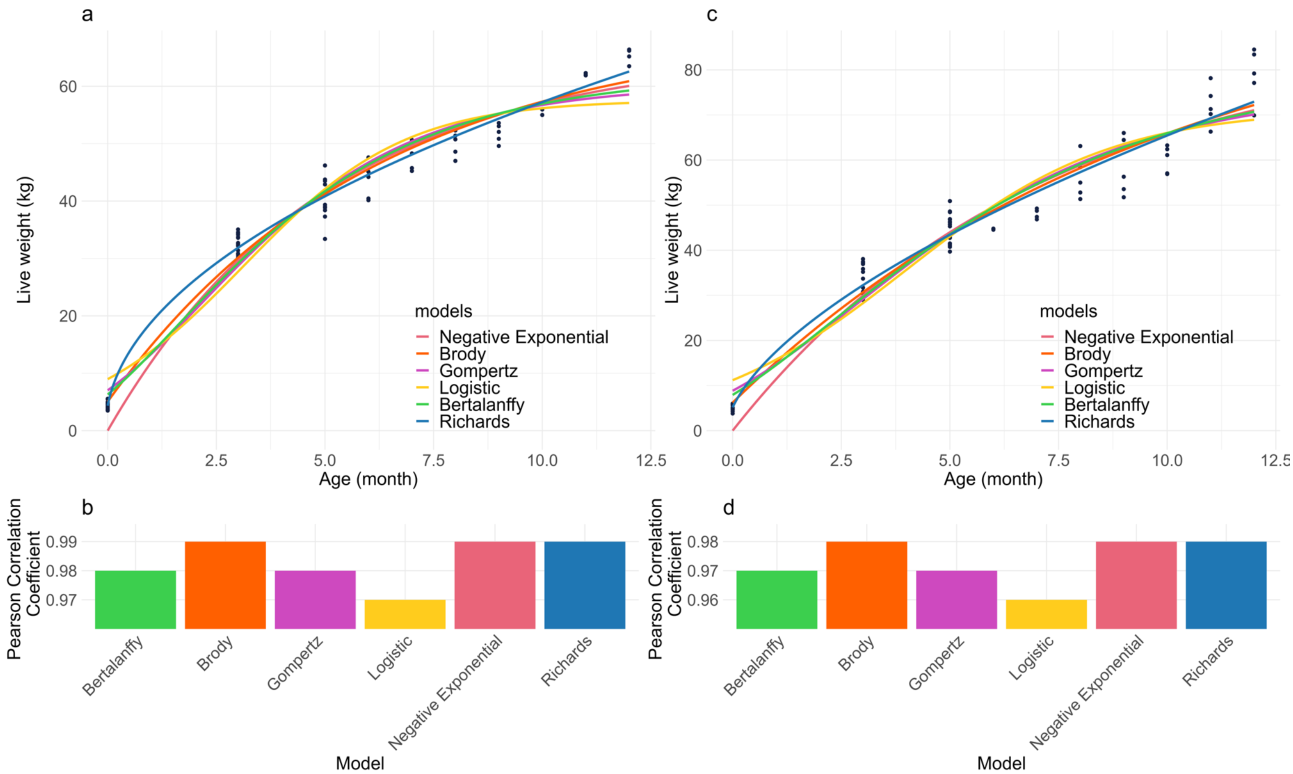

Figure 2. Growth curves of male Kıvırcık (a) and Karacabey Merino (c) lambs from birth to yearlings using different nonlinear models. Below each breed's growth curve (b, d), the Pearson correlation coefficient between the predicted and observed live weight values is given. Please note that Richards model did not achieve convergence and its inclusion on the figure is solely intended for informational purposes.

A key consideration is the parameter *k*, which reflects the maturation rate and indicates the pace of increase to attain the asymptotic weight [8]. Animals with higher *k* values reach mature weight sooner than those with lower *k* values [16]. In addition, animals with high *k* values mature earlier than those with lower *k* values while having the same birth weight [24]. The *k* values obtained from the BRO model were consistently lower for both breeds and sexes, whereas the LOG model produced the highest *k* values. Specifically, male Kıvırcık and Karacabey Merino lambs exhibited *k* values of 0.16 and 0.10, respectively, in the BRO model, while female lambs had *k* values of 0.24 and 0.16, respectively. In contrast, the LOG model yielded higher *k* values, with male Kıvırcık and Karacabey Merino lambs showing *k* values of 0.54 and 0.42, respectively, and female lambs having *k* values of 0.56 and 0.45, respectively. Greater values of the *k* parameter reported in female lambs in this study imply faster maturation rates, which aligns with the findings of Kopuzlu et al. [13] and Hossein-Zadeh [8].

Numerous studies have highlighted the inverse relationship between *A* and *k* parameters [8,24,41,51]. The correlation between the growth curve's *A* and *k* parameters is crucial from a biological standpoint. Based on this association, it appears that animals with a greater mature body weight are less likely to undergo significant weight changes after reaching adulthood than those with a lower mature body weight. In other words, the pronounced negative genetic and phenotypic correlations between parameters *A* and *k* suggest that early maturation is associated with lower mature weights. Thus, selecting for higher mature weights will likely result in a lower maturation rate [51]. On the other hand, there is evidence of a positive genetic association between growth curve parameters *A* and *B*, suggesting that a higher birth weight is related to a larger final LW in lambs [55].

The acceleration of growth and the magnitude of weight gain observed during the early stages of life are more significant than those observed during the later stages of adulthood when considering the sigmoidal growth curve pattern. As the animal develops, it undergoes a transition in growth rate, as indicated by the change in curvature, which pinpoints the inflection point corresponding to the peak growth rate [53]. As a result, growth begins to decline gradually, accompanied by a slower growth rate than in previous stages [55]. In the current study, weight and

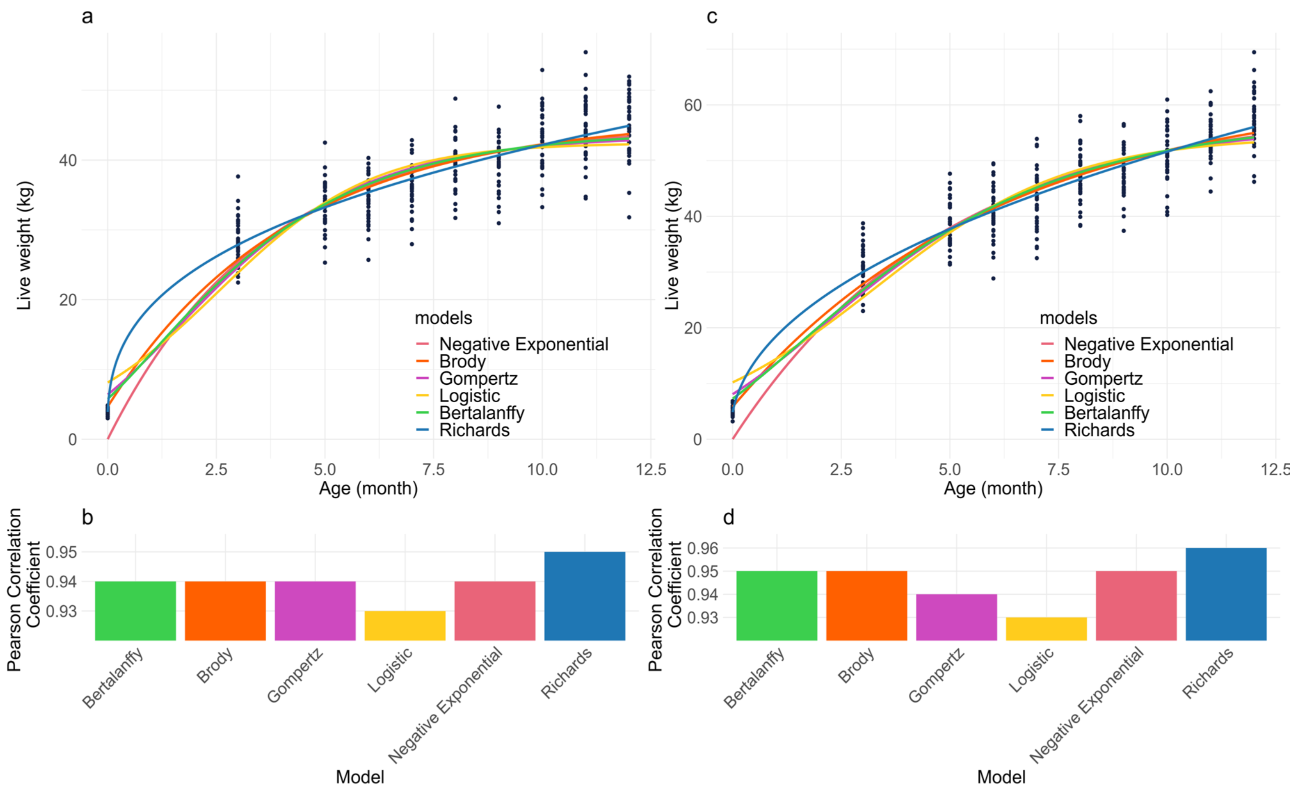

Figure 3. Growth curves of female Kıvırcık (a) and Karacabey Merino (c) lambs from birth to yearlings using different nonlinear models. Below each breed's growth curve (b, d), the Pearson correlation coefficient between the predicted and observed live weight values is given. Please note that Richards model did not achieve convergence and its inclusion on the figure is solely intended for informational purposes.

age at the inflection point were estimated as 15.84 kg and 1.45 months using the GOM model and 12.93 kg and 1.01 months using the BER model. Similarly, for Karacabey Merino lambs, the weight and age at the inflection point were estimated as 20.65 kg and 2.00 months in the GOM model, and as 17.01 kg and 1.44 months in the BER model. According to the results, Kıvırcık lambs reach the inflection point earlier and at a lower LW than Karacabey Merino lambs of the same age. Our results were comparable to those obtained from Kermani [55], Segurena [53], and Lori Bakhtiari [56] sheep breeds when employing the BER and GOM models for comparison.

It is feasible to discover early-maturing and high-performing animals by comparing observed weights with predicted weights at each age, which can considerably benefit breeding operations [7]. Furthermore, this method enables the evaluation and efficacy assessment of feeding regimens, as well as the identification of the appropriate slaughter age. Models with a considerable difference between their estimations and the actual values are often ignored in practical applications [57]. Table 4 contrasts the observed and predicted body weights of male and female lambs of the Kıvırcık and Karacabey Merino breeds for various time intervals ranging from birth to one year of age. The results show that the BRO model, regardless of sex or breed, provided the most accurate estimations for the majority of the weight measurements collected during this time period. Nevertheless, certain time periods exhibited minimal deviations. For instance, when predicting the weight of male Kıvırcık lambs at 3 months of age and 10 months of age, the NEXP and LOG models performed marginally better than the BRO models, whereas the NEXP model at 5 months of age and the BER model at 6, 9 and 10 months of age somewhat more closely forecasted the observed weight. Likewise, when predicting the weight of female Kıvırcık lambs at 6 months of age and 9 months of age, the NEXP and LOG models performed marginally better than the BRO models, respectively, whereas the NEXP model at 5 months of age and the BER model at 6 and 10 months of age, respectively, forecasted somewhat closer to the observed weight. However, these distinctions were dismissed as unimportant and trivial. The results of this study are consistent with earlier research that utilized various nonlinear models, showing that the BRO model consistently produces the most advantageous results [16,24,58]. Moreover, the BRO model generated predicted

Table 4. Observed and predicted mean weight values (kg) of Kıvırcık and Karacabey Merino lambs from birth to yearlings using different nonlinear models[1].

Sex	Breed	Model	Age (months)												
			0	1	2	3	4	5	6	7	8	9	10	11	12
M	K	OBS	4.31	-	-	32.73	-	40.76	43.50	48.08	50.01	51.83	55.63	62.13	65.33
		NEXP	0	11.99	21.81	29.85	36.43	41.81	46.23	49.84	52.79	55.22	57.20	58.82	60.15
		BRO	4.91	14.56	22.79	29.80	35.77	40.86	45.20	48.89	52.04	54.72	57.01	58.96	60.62
		GOM	7.03	13.27	20.76	28.46	35.54	41.56	46.41	50.16	52.99	55.07	56.59	57.69	58.47
		LOG	8.98	13.87	20.29	27.81	35.46	42.22	47.51	51.25	53.72	55.26	56.21	56.77	57.11
		BER	6.47	13.68	21.66	29.32	36.10	41.81	46.46	50.15	53.04	55.27	56.98	58.28	59.27
	KM	OBS	5.01	-	-	33.45	-	44.93	44.65	48.06	56.13	58.41	60.14	72.03	78.82
		NEXP	0	11.40	21.31	29.92	37.41	43.92	49.58	54.50	58.78	62.50	65.73	68.55	70.99
		BRO	6.04	15.04	23.18	30.55	37.22	43.26	48.72	53.66	58.13	62.17	65.83	69.14	72.14
		GOM	8.81	14.69	21.70	29.22	36.68	43.64	49.82	55.12	59.55	63.16	66.07	68.38	70.19
		LOG	11.19	15.75	21.49	28.26	35.64	43.02	49.80	55.54	60.10	63.52	66.00	67.73	68.91
		BER	7.80	14.25	21.53	28.98	36.15	42.76	48.68	53.86	58.31	62.10	65.29	67.95	70.16
F	K	OBS	3.91	-	-	28.70	-	33.57	34.28	36.46	39.68	39.16	42.93	44.42	45.03
		NEXP	0	10.98	19.28	25.55	30.29	33.87	36.58	38.63	40.17	41.34	42.23	42.89	43.40
		BRO	4.62	13.48	20.45	25.93	30.25	33.64	36.31	38.41	40.06	41.36	42.38	43.19	43.82
		GOM	6.37	12.15	18.65	24.79	29.94	33.93	36.88	38.97	40.42	41.42	42.09	42.54	42.85
		LOG	8.13	12.45	17.86	23.77	29.30	33.79	37.03	39.18	40.52	41.33	41.81	42.08	42.24
		BER	5.84	12.36	19.09	25.06	29.94	33.74	36.60	38.70	40.24	41.34	42.13	42.70	43.10
	KM	OBS	4.82	-	-	30.62	-	38.89	40.63	42.71	47.03	47.45	50.76	54.29	57.94
		NEXP	0	10.81	19.66	26.90	32.83	37.69	41.66	44.92	47.58	49.76	51.55	53.01	54.21
		BRO	5.69	14.20	21.45	27.63	32.90	37.39	41.21	44.47	47.25	49.61	51.63	53.35	54.81
		GOM	8.10	13.59	19.86	26.23	32.17	37.36	41.69	45.19	47.93	50.06	51.67	52.89	53.80
		LOG	10.20	14.45	19.69	25.61	31.68	37.33	42.11	45.85	48.61	50.55	51.87	52.74	53.32
		BER	7.22	13.40	20.04	26.44	32.22	37.21	41.39	44.81	47.58	49.79	51.54	52.92	54.00

[1]The calculation could not be performed due to the lack of convergence in the Richards model. M: Male; F: Female; K: Kıvırcık; KM: Karacabey Merino; OBS: Observed; NEXP: Negative exponential; BRO: Brody; GOM: Gompertz; LOG: Logistic; BER: Bertalanffy.

values that closely matched the actual data for both breeds and sexes, corroborating previous observations made in the case of the Kıvırcık breed [47]. Furthermore, our findings support Mohammadi et al. [44] and Gbangboche et al. [23]'s findings of a positive relationship between age and body weight in both male and female lambs, with male lambs consistently having larger body weights than female lambs.

Comparing Kıvırcık and Karacabey Merino lambs, differences in the time required to attain the optimal slaughter ages were observed. Table 5 shows the comparisons between the observed data and predicted values from the NEXP, BRO, GOM, LOG, and BER models. In general, the BRO model achieved projected values that were consistently closer to the observed data for the majority of the lowest and maximum durations across a variety of breeds and sexes. Furthermore, the results obtained from all the models used for male Kıvırcık and Karacabey Merino lambs are consistent with the prevailing slaughter age standards implemented by producers nationwide. However, modest variations have been noticed among the models across specific breed and sex combinations. The NEXP and GOM models aligned better with the observed data, most notably in the Karacabey Merino breed. The LOG model had the most differences, particularly for female Karacabey Merino lambs. These findings highlight the significance of using an appropriate growth curve model to accurately predict the time required to reach the optimal slaughter weight in various lamb populations, which is also aligns with several previous reports [51,59,60].

4. Conclusion

The importance of selecting the appropriate growth curve models and conducting extra nonlinear research underlines the importance of having a thorough understanding of sheep breed development. In the current study, The BRO model was able to successfully forecast the growth curves for both male and female lambs, and these predictions were consistent with common slaughter methods. Consequently, these findings improve our understanding

Table 5. Assessment of slaughter ages in Kıvırcık and Karacabey Merino lambs by different nonlinear models[1,2].

Model	Kıvırcık				Karacabey Merino			
	Male		Female		Male		Female	
	Min (d)	Max (d)	Min (d)	Max (d)	Min (d)	Max (d)	Min (d)	Max (d)
OBS	144	190	277	359	124	157	169	226
NEXP	140	172	237	454	132	156	167	211
BRO	145	179	239	416	134	160	171	218
GOM	142	171	231	569	134	157	168	208
LOG	140	166	228	880	138	159	167	203
BER	140	171	235	503	138	161	170	212

[1]Lambs were considered ready for slaughter when they reached a minimum of 40 kg and a maximum of 45 kg in live weight. [2] The calculation could not be performed due to the lack of convergence in the Richards model. OBS: Observed; NEXP: Negative exponential; BRO: Brody; GOM: Gompertz; LOG: Logistic; BER: Bertalanffy; d: Day.

of sheep dynamics, allowing us to make better decisions regarding breeding and commercial operations in terms of lamb growth trends, maturation rates, and mature weights.

Conflict of interest

The authors declare that they have no competing interests.

Compliance with ethical standard

The animal care and handling procedures were reviewed and approved by the Ethical Committee of the Sheep Breeding Research Institute (approval number:13360037).

Acknowledgment

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