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Comparison of non-linear models and genetic parameter estimation for growth curve traits in the Murciano-Granadina goat breed

M. Mokhtari [a,*], A. Esmailizadeh [b], R. Mirmahmoudi [a], J.P. Gutierrez [c], E. Mohebbinejad [d]

[a] Department of Animal Science, Faculty of Agriculture, University of Jiroft, Jiroft, Iran
[b] Department of Animal Science, Faculty of Agriculture, Shahid Bahonar University of Kerman, Kerman, Iran
[c] Departamento de Produccion Animal, Universidad Complutense de Madrid, Avda. Puerta de Hierro s/n, E-28040 Madrid, Spain
[d] Ghale-Ganj dairy farm, Fajr Isfahan Agricultural and Livestock Company, Isfahan, Iran

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ABSTRACT

In this study, we analyzed 50,238 records of the body weight of the Murciano-Granadina goat breed from birth to 360 days of age. The data were collected from a private dairy farm located in Ghale-Ganj city, which is in the southern part of Kerman province, in the south of Iran. The records were collected between 2016 and 2022. Our goal was to evaluate the suitability of non-linear models for characterizing growth curves from birth to 360 days of age and to estimate genetic parameters for these growth curve traits. Five non-linear mathematical models namely Brody, Negative exponential, von Bertalanffy, Logistic, and Gompertz were compared by using Akaike's information criterion (AIC), root mean square error (RMSE), and Durbin-Watson statistic (DW) to determine the most suitable function for characterizing the growth curve. Among the investigated models, the von Bertalanffy model exhibited the lowest values for both AIC and RMSE. Additionally, we observed positive autocorrelations among residuals for all of the investigated non-linear models, with the lowest value being observed for the von Bertalanffy model. As a result, we selected the von Bertalanffy as the most suitable model for characterizing the growth curve of the Murciano-Granadina goat breed. To estimate genetic parameters for the growth curve traits, including parameters A (estimated mature weight), B (an integration constant related to initial animal weight), K (maturation rate), inflection age (IA), and inflection weight (IW), we utilized a Bayesian multivariate animal model that accounted only for direct additive genetic effects. The posterior means for heritabilities of A, B, K, IA, and IW were significant values of 0.11, 0.13, 0.03, 0.11, and 0.17, respectively. Parameter A had significant and positive genetic and phenotypic correlations with parameters B, IA, and IW. The posterior means for genetic and phenotypic correlations between parameters A and K were negative estimates of − 0.58 and − 0.17, respectively, implying that the kids with slower maturation rates had higher mature weights. Positive and medium estimates were obtained for posterior means of phenotypic (0.04) and genetic (0.29) correlations between parameters B and K. Both posterior means for phenotypic and genetic correlations of B with IA were 0.32 while those of B with IW were 0.51 and 0.50, respectively. We found high and positive genetic (0.51) and phenotypic (0.50) correlations between IA and IW. However, we observed low levels of additive genetic variation for all of the studied growth curve traits. In conclusion, our analysis suggests that the growth curve traits of the Murciano-Granadina goat breed are highly influenced by non-additive genetic and environmental effects. Therefore, it is essential to consider these effects when designing strategies to improve these traits and develop an appropriate breeding scheme that can achieve the desired shape of the growth curve.

1. Introduction

The increase in body weight and size over time, commonly referred to as growth, is a fundamental aspect of animal development (Bathaei and Leroy, 1998). Livestock growth is a crucial economic characteristic that can be mathematically modeled to explain this biological phenomenon (Eisen, 1976). Growth curves have three phases including preparing, increasing, and quietness. According to Waheed et al. (2011), growth can be divided into three phases. During the first phase, growth begins at a specific point and gradually increases. The second phase is

* Correspondence to: Department of Animal Science, Faculty of Agriculture, University of Jiroft, P.O. Box 364, Jiroft, Iran.
E-mail address: msmokhtari@ujiroft.ac.ir (M. Mokhtari).

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characterized by a partially linear shape of the growth curve until it reaches the inflection point. Finally, in the third phase, the growth curve approaches an asymptote. As Ghavi Hossein-Zadeh (2017) pointed out, monitoring the growth of livestock throughout their lifetime is critical for suggesting appropriate feeding procedures based on their weight and determining the optimal slaughter age. Additionally, the growth curve can be used to inform management practices on the farm, such as culling low-productive animals and selecting high-productive ones by considering their growth curve. Similarly, Waheed et al. (2011) highlighted the importance of the growth curve in developing managerial practices on the farm. On the other hand, a slow growth rate of animals can lead to lower market weight and reduced profitability of breeding practices in any production system (Abegaz et al., 2010). Non-linear models have been extensively studied as a suitable tool for characterizing the growth curve in livestock (Malhado et al., 2009). The ability of these models to quantify biological parameters of growth, such as mature weight, is crucial (Teleken et al., 2017). Furthermore, the mathematical models used for modeling the growth curve of livestock can be viewed as tools for controlling and optimizing livestock production systems (Vazquez et al., 2012). Several non-linear mathematical models such as negative exponential (Brown et al., 1976), Brody (Brody, 1945), Gompertz (Laird, 1965), Logistic (Nelder, 1961), von Bertalanffy (von Bertalanffy, 1957) and Richards (Richards, 1959) have been applied for describing the growth curve in domestic animals. The growth curve parameters in Beetal goats of Pakistan have been estimated by Waheed et al. (2011) by applying the Brody and Gompertz models. They reported that any of these models can be considered to estimate the growth curve of this breed. Some studies reported that the Gompertz model is a suitable model for describing the growth curves in some goat breeds (Sghaier et al., 2007; Kume and Hajno, 2011; Gaddour et al., 2012; Ghiasi et al., 2018).

To increase the incomes of goat flock holders in many less-developed countries, both governmental and non-governmental organizations involved in rural development programs have recommended the use of high-yielding foreign dairy goat breeds (Serradilla, 2001). These programs aim to either establish milk production where goats were not previously milked or increase milk yields where they were previously very low (Serradilla, 2001). The Murciano-Granadina is one of the most well-known dairy goat breeds in Spain. This breed can be kept in production in variable situations, from dry and hot areas to cold and mountainous ones (Delgado et al., 2017). The Murciano-Granadina goat breed was synthesized in 1975 from the Murciana and Granadina goat breeds in the semi-arid areas in southeastern Spain. The main phenotypic characteristics of the Murciano-Granadina goat breed are included a straight or sub-concave profile, and a medium-sized body with a tendency to lengthen with black or brown uniform coat color, 77 cm and 70 cm high at the withers in males and females, respectively (Delgado et al., 2017). The commercial capabilities of this breed give evidence of the far-reaching process that the population has undergone in recent decades to most parts of the world from the Mediterranean basin and North Africa to Iberoamerican countries (Martínez et al., 2011).

In 2015, the private sector imported 3000 Murciano-Granadina goats from Spain to the southern region of Iran. This initiative aimed to improve the production efficiency of low-input and low-output local goat breeding farms and enhance the livelihoods of rural flock holders in the southern parts of the country. To achieve this goal, purebred Murciano-Granadina does and bucks were distributed to local flocks or used for crossbreeding with local goat breeds in the region. In Iran, local farmers typically keep goat breeds for their multi-purpose (fiber, meat, and milk) capabilities. While the Murciano-Granadina goat breed is primarily used for dairy production, understanding the genetic and phenotypic aspects of growth performance in this breed can provide valuable information for developing an appropriate breeding strategy that incorporates both Murciano-Granadina and local goat breeds in the future. The main objective of this study was to compare five different non-linear mathematical models used to characterize the growth pattern of the Murciano-Granadina goat breed and to conduct a genetic evaluation of the growth curve traits investigated in the study.

2. Materials and methods

2.1. Data and flock management

The Murciano-Granadina goat flock used in this study was kept under an intensive production system. New-born kids were weighed and ear-tagged at birth time. Furthermore, related information on the sex and birth type of newborn kids and also the identities of the dam and sire of each kid were recorded. Weaning was at about 80 days of age. Kids were kept indoors and manually fed. Maiden does were exposed to the fertile bucks at approximately 11 months of age and 25 kg live body weights in separate groups with a ratio of 15 does per each fertile buck. In the current study, 50238 body weight-age records (17239 records on male kids and 32999 records on female kids) were collected from 2016 to 2022 in a private dairy farm, located in Ghale-Ganj city, south of Kerman province, south area of Iran, used. Records were related to 16020 kids descended from 343 sires and 4304 dams. Records included monthly body weights from birth until 360 days of age.

The ENDOG v4.8 program was used for checking errors in the pedigree and preparing it for subsequent analyses (Gutierrez and Goyache, 2005). The pedigree structure of the studied population of the Murciano-Granadina goat is shown in Table 1. Among the registered goats, individuals with both parents known, both parents unknown, and one parent known comprised 88.18%, 10.50%, and 1.32% of all individuals, respectively. About, 68.58% of animals had no progeny, while 31.42% had progeny.

2.2. The investigated non-linear mathematical models

To determine the most suitable mathematical function characterizing the growth curve of the Murciano-Granadina goat breed, five non-linear models including Logistic, Gompertz, Brody, Negative exponential, and von Bertalanffy were fitted on live body weight-age records. The mathematical representations of the investigated non-linear models were as follows:

$y = A/(1 + Be^{-Kt})$	Logistic model
$y = Ae^{-Be^{-Kt}}$	Gompertz model
$y = A(1 - Be^{-Kt})$	Brody model
$y = A - (Ae^{-Kt})$	Negative exponential model
$y = A(1 - Be^{-Kt})^3$	von Bertalanffy model

In which, y is live body weight at age t (in days), A is the asymptotic weight which is interpreted as mature weight, B is an integration constant related to initial animal body weight, K is maturation rate and e is the base of the natural logarithm. Live body weight-age records were

Table 1
Pedigree structure of the population of Murciano-Granadina goat.

Item	Numbers
Individuals in total	21785
Inbreds in total	813
Sires in total	448
Dams in total	6398
Individuals with progeny	6846
Individuals with no progeny	14939
Founders	2288
Individuals with both parents known	19211
Individuals with both parents unknown	2288
Individuals with one parent unknown	286
Average inbreeding coefficients (%)	0.20
Average inbreeding coefficients in the inbreds (%)	6.8
Maximum of inbreeding coefficients (%)	31.25
Minimum of inbreeding coefficients (%)	0.39

analyzed by applying the NLIN procedure and Newton-Gauss iterative method (SAS, 2004). The investigated non-linear mathematical models were compared utilizing three statistical measures including Akaike's information criterion (AIC), root mean square error (RMSE), and Durbin-Watson statistic (DW). Model fitting and comparisons were done by applying SAS 9.4 software (SAS, 2004). The first measure was Akaike's information criterion and was calculated as follows:

$$AIC = n\log(\frac{SSe}{n}) + 2p$$

The second comparative measure, RMSE, was calculated as follows:

$$RMSE = \sqrt{\frac{SS_e}{n-p-1}}$$

In these comparison measures, n is the number of records, p is the number of model parameters and SS_e is the residual sum of squares. The third comparative measure was the Durbin-Watson (DW) statistic which was computed by applying the following formula (Durbin, 1970):

$$DW = \frac{\Sigma_{e=2}^{n}(e_t - e_{t-1})^2}{\Sigma_{t=1}^{n} e_t^2}$$

where e_t is the residual at time t, and e_{t-1} is the residual at time t-1. The existence of autocorrelation in the residuals from the regression analysis may be assessed by applying DW. The DW statistic varies from 0 to 4. A value near 2 shows the absence of autocorrelation, a value toward 0 denotes a positive autocorrelation and a value toward 4 denotes a negative autocorrelation (Durbin, 1970).

In model comparison, it is customary to consider the model with the lowest AIC and RMSE to be the most suitable (fit) among the investigated models. After determining the best non-linear function, the inflection weight (IW) and inflection age (IA) were obtained as follows (Lupi et al., 2016):

IW= 8 A / 27.

and.

IA= ln (3B) / K.

A, B, and K are as defined previously.

2.3. The estimation of (co)variance components and genetic parameters

The model included direct additive genetic and residual effects as random ones performed better than the models that included different combinations of maternal additive genetic, maternal permanent environmental, and co-variance between direct-maternal genetic effects. The comparisons of the models regarding the importance of maternal effects on the studied growth curve traits were not shown. The estimation of (co)variance components and genetic parameters for the studied growth curve traits was done by applying a Bayesian multivariate animal model as follows:

$$y_i = X_i\, b_i + Z_{1i}\, a_i + ei$$

Where, $\mathbf{y_i}$ is a vector of estimated individual values for the studied growth curve traits; $\mathbf{b}_i$, $\mathbf{a_i}$, and $\mathbf{e_i}$ are vectors of systematic, direct genetic, and residual effects for trait i, respectively. The fixed effects tested for including in the multivariate animal model were the sex of kids in 2 classes (males and females), dam age at kidding in 5 classes (1–5 years old), birth type in 2 classes (single and twin), birth year in 7 classes (2016–2022), and birth month in 12 classes. Multivariate normal distribution with a null mean vector and a (co)variance matrix $\mathbf{G} \otimes \mathbf{A}$, was assumed for the direct additive genetic effects. Where **G** and **A** are the additive genetic (co)variance and numerator relationship matrices among kids, respectively. Also, multivariate normal distribution with a null mean vector and (co)variance matrix $\mathbf{R} \otimes \mathbf{I_n}$, was assumed for the residual effects. Where $\mathbf{I_n}$ and **R** are the identity residual (co)variance matrices, respectively; $\otimes$ shows the Kronecker product.

Genetic analysis for estimating posterior means of (co)variance components and genetic parameters was accomplished by using the GIBBS2F90 program (Misztal et al., 2002). The length of the chain and the burn-in period were evaluated by visual inspection of the trace plots of posterior samples of the parameters.

In total, 100,000 iterations were run with thinning intervals of 10 iterations. The first 20,000 iterations were considered a burn-in period. Therefore, 4000 samples were kept for the subsequent analyses. The POSTGIBBSF90 program (Misztal et al., 2002) was used for calculating posterior means and posterior standard deviations (PSD) of (co)variance components and the estimates of genetic parameters for the studied growth curve traits.

The GLM procedure of SAS 9.4 software (SAS, 2004) was applied for determining the significant fixed effects to be considered in the model.

3. Results and discussion

3.1. The comparisons of the investigated non-linear models

The outcomes of model comparisons for the growth curve of Murciano-Granadina kids under the five investigated non-linear mathematical models are shown in Table 2. According to the lowest both AIC and RMSE values and also DW statistic, the von Bertalanffy model was determined as the most appropriate model for describing the growth curve in Murciano-Granadina kids. The Gompertz had the highest AIC and RMSE over other tested models and showed the worst performance for describing the growth curve of Murciano-Granadina kids among the tested models.

Literature shows high variability in the performance of different curve growth model definitions. Ozdemir and Dellal (2009) analyzed the growth curves of young Angora goats by using Logistic and Gompertz models and concluded that both models were suitable to define the time-dependent changes in the live weights from birth to yearling age in young Angora goats. Waheed et al. (2011) applied Brody and Gompertz mathematical models for describing the growth curve and estimating the corresponding parameters in Beetal goats of Pakistan. They reported that both considered non-linear models described the growth curve in this breed appropriately.

Chacara Pires et al. (2017) fitted five non-linear models of Brody, Gompertz, logistic, von Bertalanffy, and Richards on body weight-age records of Repartida goats of Brazil, collected from birth to 270 days of age, and concluded that the Logistic model showed the best fit for describing growth curve. Kheirabadi and Rashidi (2019) compared five non-linear models including Brody, von Bertalanffy, Richards, Gompertz, and Logistic for investigating the best description of the growth patterns of Markhoz kids and concluded that the Brody model best fit the data.

Waiz et al. (2019) compared five non-linear mixed growth curve models to describe the growth trajectory of the Sirohi goat breed from birth to 12 months of age and concluded that the Brody model was favorable for modeling growth curves in both male and Sirohi kids. Gautam et al. (2019) fitted four non-linear models including Gompertz, Brody, Logistic, and von Bertalanffy on live body weight-age records in Sirohi goats and reported that Brody fitted growth curve in this breed more appropriately than the other studied models. Magotra et al. (2021) studied the suitability of five growth curve models including Brody, Gompertz, Logistic, Bertalanffy, and Negative exponential for describing the growth trajectory of the Beetal goat breed in India. The comparative study based on goodness fit measures revealed that the Brody model was the most suitable function for describing the growth curve in this breed. The observed and predicted averaged body weights from birth to 360 days of age obtained by fitting the von Bertalanffy model are presented in Fig. 1. There was an increasing trend for body weights along with increases in the ages of kids.

Estimates of model parameters of the growth curve in the Murciano-Granadina goat under the investigated non-linear models are shown in

Table 2
Comparative statistics for goodness of fit measures and estimates of model parameters (± standard error) of the growth curve across the tested growth curves in the Murciano-Granadina kids.

Function	Comparative measures[¥]			Model parameters[¥¥]		
	AIC	RMSE	DW	A	B	K
Brody	54.334	0.962	1.784	34.26 ± 3.85	0.89 ± 0.02	0.003 ± 0.0007
Negative exponential	64.397	1.253	1.414	27.82 ± 1.89	-	0.006 ± 0.0008
von Bertalanffy	53.937	0.932	1.934	29.06 ± 1.83	0.47 ± 0.02	0.006 ± 0.0008
Gompertz	127.598	6.775	1.054	NC	NC	NC
Logistic	89.593	2.433	1.302	NC	NC	NC

[¥]AIC: Akaike's information criterion, RMSE: Root mean square error, DW: Durbin-Watson statistic
[¥¥]A: Asymptotic weight which is considered as mature weight, B: An integration constant related to initial animal weight, K: Maturation rate, m: is the parameter that gives shape to the curve by indicating where the inflection point occurs.
NC: Not converged

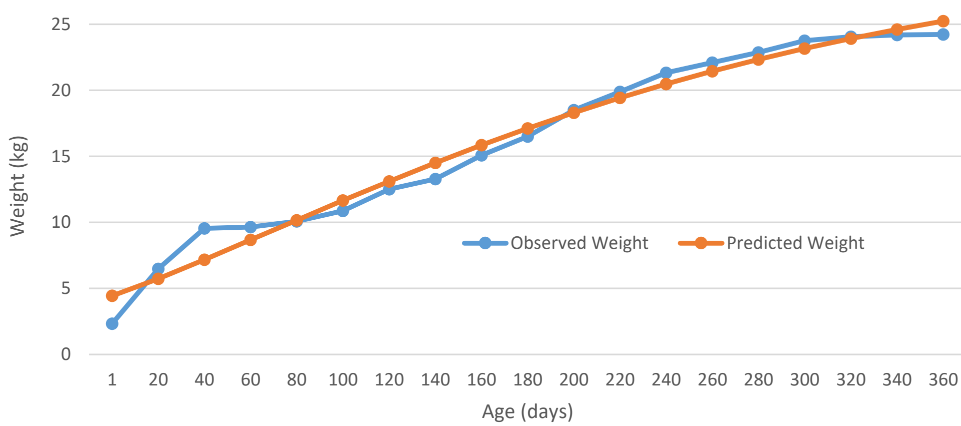

Fig. 1. Observed and predicted body weights (kg) of the Murciano-Granadina goat at different ages by von Bertalanffy model.

Table 2. In the present study, by fitting the von Bertalanffy model, the estimated values for growth curve parameters including parameters A, B, and K were obtained at 29.06 kg, 0.47, and 0.006, respectively.

Parameter A is considered an estimate of mature body weight. Malhado et al. (2009) remembered that the definition of an optimum mature weight is problematic as it depends on several factors such as species, breed, managerial practices, and environmental conditions. Ozdemir and Dellal (2009) reported values of 20.70 and 23.39 for parameter A in Angora goats under the Logistic and Gompertz models, respectively. Waheed et al. (2011) reported values of 29.13 kg and 23.39 kg for parameter A in Beetal kids under Brody and Gompertz models, respectively. In another study, Ghiasi et al. (2018) estimated a value of 17.97 kg for parameter A in Raeini Cashmere goat under the Gompertz model which is lower than the corresponding estimated value in the present study. By fitting the Brody function, Kheirabadi and Rashidi (2019) and Magotra et al. (2021) obtained values of 30.50 and 28.21 kg for parameter A in Markhoz goat and Beetal goat breeds, respectively which are in agreement with the corresponding estimated value in the present study (29.06 kg).

Malhado et al. (2009) pointed out that parameter B is an integration constant without a certain biological interpretation. The estimate of parameter B in the present study (0.47 kg) was lower than those obtained by Ghiasi et al. (2018) in the Raeini Cashmere goat breed under the Gompertz model (1.97 kg), by Kheirabadi and Rashidi (2019) in the Markhoz goat breed under Brody model (0.91), by Waheed et al. (2011) in Beetal goat of Pakistan under Brody (0.916) and Gompertz (1.980) models, and by Magotra et al. (2021) in Beetal goat of India under Brody model (0.91).

Lupi et al. (2016) pointed out that animals with higher values for parameter K gain maturity weight faster than the animals with the lower corresponding values. The estimated value for parameter K in the present study (0.006) was consistent with the values estimated by Kheirabadi and Rashidi (2019) in Markhoz goat (0.007) and by Ozdemir and Dellal (2009) in Angora goat (0.0069) breeds under Brody and Gompertz models, respectively. Higher estimates were obtained by Waheed et al. (2011) in the Beetal goat of Pakistan under the Brody (0.108) and Gompertz (0.258) models and by Magotra et al. (2021) in the Beetal goat of India under the Brody model (0.13).

3.2. Non-genetic effects influencing the studied growth curve traits

Descriptive statistics for the studied growth curve traits, obtained by fitting the von Bertalanffy model are shown in Table 3. The lowest and highest coefficient of variations were obtained for parameter B and IA, respectively. The least squares means of the studied growth curve traits of Murciano-Granadina goat across the levels of the considered fixed effects are shown in Table 4.

The birth year of kids significantly influenced all the studied growth

Table 3
Descriptive statistics for the studied growth curve traits in Murciano-Granadina goat.

Item[¥]	Traits[¥¥]				
	A	B	K	IW	IA
Mean	29.04	0.54	0.0073	8.61	69.76
S.D.	2.98	0.02	0.0014	0.88	15.80
C.V. (%)	10.26	3.70	19.18	10.22	22.65
Min.	23.58	0.44	0.0036	6.99	41.69
Max.	34.55	0.58	0.0098	10.24	142.03

[¥] S.D.: standard deviation, C.V.: coefficient of variation, Min.: minimum value, Max.: maximum value
[¥¥]A: asymptotic weight which is interpreted as mature weight, B: an integration constant related to initial animal weight, K: maturation rate, IA: Inflection age, IW: Inflection weight.

Table 4
Least squares means (± S.E.) for the studied growth curve traits of the Murciano-Granadina goat breed.

Effect	Traits[¥] A	B	K	IW	IA
Sex	* *	* *	* *	* *	* *
Male	29.19 $\pm 0.14^{a}$	0.55 $\pm 0.001^{a}$	0.006 $\pm 0.000^{b}$	8.65 $\pm 0.04^{a}$	63.43 $\pm 1.01^{b}$
Female	27.95 $\pm 0.20^{b}$	0.54 $\pm 0.001^{b}$	0.008 $\pm 0.000^{a}$	7.58 $\pm 0.06^{b}$	73.78 $\pm 0.72^{a}$
Birth type	ns	ns	ns	ns	ns
Single	29.15 $\pm 0.17^{a}$	0.55 $\pm 0.001^{a}$	0.007 $\pm 0.000^{a}$	8.64 $\pm 0.05^{a}$	68.11 $\pm 0.87^{a}$
Twin	28.98 $\pm 0.16^{a}$	0.55 $\pm 0.001^{a}$	0.007 $\pm 0.000^{a}$	8.59 $\pm 0.05^{a}$	69.10 $\pm 0.80^{a}$
Dam age (yr)	*	ns	ns	*	ns
1	28.73 $\pm 0.26^{b}$	0.55 $\pm 0.002^{a}$	0.007 $\pm 0.000^{a}$	8.51 $\pm 0.08^{b}$	68.64 $\pm 1.03^{a}$
2	28.61 $\pm 0.20^{b}$	0.54 $\pm 0.001^{a}$	0.007 $\pm 0.000^{a}$	8.66 $\pm 0.06^{b}$	68.76 $\pm 0.99^{a}$
3	28.97 $\pm 0.22^{b}$	0.54 $\pm 0.001^{a}$	0.007 $\pm 0.000^{a}$	8.58 $\pm 0.06^{b}$	68.92 $\pm 1.09^{a}$
4	28.64 $\pm 0.27^{b}$	0.54 $\pm 0.002^{a}$	0.007 $\pm 0.000^{a}$	8.49 $\pm 0.08^{b}$	68.85 $\pm 1.34^{a}$
5	29.79 $\pm 0.39^{a}$	0.55 $\pm 0.003^{a}$	0.007 $\pm 0.000^{a}$	8.83 $\pm 0.11^{a}$	69.88 $\pm 1.96^{a}$
Birth month	ns	* *	* *	ns	ns
Birth year	* *	* *	* *	* *	* *

[¥]A: asymptotic weight which is interpreted as mature weight, B: an integration constant related to initial animal weight, K: maturation rate, IA: Inflection age, IW: Inflection weight

Means with similar letters in each sub-class within a column do not differ from another at $p < 0.05$, ns: not significant. Means with different letters in each sub-class within a column differ from another at * $p < 0.05$ and * * $p < 0.01$.

curve traits ($p < 0.01$) which may be justified by variations in climatic conditions and managerial practices through the years (Gbangboche et al., 2008). The birth month had significant effects on parameters B and K of Murciano-Granadina kids ($p < 0.01$) but not on parameter A, IW, and IA ($p > 0.05$).

The sex of kids significantly influenced all the studied growth curve traits ($p < 0.01$). Male kids were superior in all the studied traits to female ones. The effect of the sex of kids on the growth curve traits could be related to the hormonal and physiological variations between male and female animals (Ebangi et al., 1996). Contrary to our results, Ghiasi et al. (2018) reported no sexual differences between growth curve traits including parameters A, B, and K, IA, and IW in the Raeini Cashmere goat breed. Also, Waheed et al. (2011) reported that the sex of kids had no significant effects on the growth curve parameters in Beetal goats of Pakistan.

The birth type of Murciano-Granadina kids had no significant effects on all the studied growth curve traits ($p > 0.05$). In other words, there were no statistically significant differences between growth curve traits of single- and twin-born Murciano-Granadina kids. Contrary to us, Ghiasi et al. (2018) reported that the birth type of Raeini Cashmere kids had no significant effects on the studied growth curve traits. By fitting the Gompertz model, Kume and Hajno (2011) studied the growth curve variations of Alpine goats and reported that the birth type of kids had significant effects on parameters A, B and K. Dam age had a significant influence on parameter A and IW of Murciano-Granadina kids ($p < 0.05$) but not on the other growth curve traits ($p > 0.05$). The highest values for parameter A and IW were observed in kids born from five years old does.

3.3. Genetic parameters

3.3.1. Posterior means of heritabilities

Posterior means and posterior standard deviations of heritabilities for the studied growth curve traits of the Murciano-Granadina goat breed are presented in Table 5. The corresponding posterior means for heritabilities were 0.11, 0.13, 0.03, 0.11, and 0.17 for parameters A, B, K, IA, and IW respectively. The posterior means for heritabilities of the growth curve traits were statistically significant. The low direct heritability estimates may be justified by the large environmental variance of the traits investigated. Therefore, the improvement of these traits could be obtained partly by improving environmental conditions rather than direct genetic selection. Generally, factors such as breed, within-population genetic variations, fitted models, and methods used for estimating the parameters and management conditions affect the estimation of heritability for the growth curve parameters (Ghavi Hossein-Zadeh, 2017).

By considering the Gompertz model for describing the growth curve pattern, Ghiasi et al. (2018) reported estimates of 0.14, 0.10, 0.03, 0.14, and 0.14 for heritability of parameters A, B, K, IA, and IW in Raeini Cashmere goat, respectively. Lupi et al. (2016) reported direct heritability estimates of 0.41, 0.51, 0.62, 0.41, and 0.41 for A, B, P, IW, and IA in the Segurena sheep breed, respectively, which were higher than the corresponding values estimated in the present study. Fitting the Brody model, Kheirabadi and Rashidi (2019) obtained estimates of 0.067, 0.063, and 0.044 for the heritability of parameters A, B, and K in the Markhoz goat breed, respectively. Estimates of 0.10, 0.05, and 0.27 were obtained by Magotra et al. (2021) for the heritability of parameters A, B, and K in the Beetal goats of India.

3.3.2. Genetic and phenotypic correlations

Posterior means and posterior standard deviations for genetic and phenotypic correlations among the studied growth curve traits of the Murciano-Granadina goat are presented in Table 5. Posterior means of genetic correlations among the studied growth curve traits ranged from − 0.90 for K-IW to 0.95 for A-IA while the phenotypic correlations ranged from − 0.36 for K-IW to 0.93 for A-IA.

In the present study, positive and medium estimates were obtained for phenotypic (0.32) and genetic (0.32) correlations between parameters A and B. In other words, because of the positive genetic and phenotypic correlations between parameters A and B, any increase in the initial body weight of kids could be associated correspondingly with the increase in mature live weight. Ghiasi et al. (2018) reported values of 0.73 and 0.69 for genetic and phenotypic correlations between parameters A and B in Raeini Cashmere goat which were higher than the corresponding estimated values in the present study. High estimates of 0.993 and 0.976 were also obtained by Kheirabadi and Rashidi (2019) for genetic and phenotypic correlation between parameters A and B in

Table 5
Posterior means ± posterior standard deviation for heritabilities(on diagonal), genetic (above diagonal), and phenotypic (below diagonal) correlations between the studied growth curve traits in the Murciano-Granadina goat.

Traits[¥]	A	B	K	IA	IW
A	0.11 ± 0.04	0.32 ± 0.08	-0.58 ± 0.21	0.95 ± 0.01	0.50 ± 0.22
B	0.32 ± 0.02	0.13 ± 0.05	0.29 ± 0.08	0.32 ± 0.08	0.38 ± 0.15
K	-0.17 ± 0.02	0.04 ± 0.02	0.03 ± 0.01	-0.58 ± 0.21	-0.90 ± 0.08
IA	0.93 ± 0.02	0.32 ± 0.02	-0.17 ± 0.02	0.11 ± 0.05	0.50 ± 0.22
IW	0.51 ± 0.02	0.33 ± 0.02	-0.36 ± 0.04	0.51 ± 0.02	0.17 ± 0.06

[¥] A: asymptotic weight which is interpreted as mature weight, B: an integration constant related to initial animal weight, K: maturation rate, IA: Inflection age, IW: Inflection weight.

the Markhoz goats, respectively. Magotra et al. (2021) reported high estimates of 0.96 and 0.68 for genetic and phenotypic correlations of parameters A and B in the Beetal goats of India, respectively.

Genetic and phenotypic correlations between parameters A and K were estimated at − 0.58 and − 0.17, respectively, implying that Murciano-Granadina kids with faster growth rates were less likely to achieve as large a mature weight as kids that grew more slowly in early life. From a biological point of view, the correlation between parameters A and K is important. da Silva et al. (2012) pointed out that the negative correlation estimate between parameters A and K denoted that animals with higher mature body weights generally show lower body weight modification with adult weight than animals with a lower mature weight. Negative estimates of − 0.36 and − 0.15 were also reported by Ghiasi et al. (2018) for genetic and phenotypic correlation between parameters A and K in the Raeini Cashmere goat breed. Kheirabadi and Rashidi (2019) also reported estimates of − 0.866 and − 0.723 for genetic and phenotypic correlations between parameters A and K in the Markhoz goats. Similarly, Magotra et al. (2021) estimated values of − 0.99 and − 0.63 for genetic and phenotypic correlations between parameters A and K in the Beetal goat of India, respectively.

The posterior means for genetic correlations of parameter A with IA and IW were 0.95 and 0.50, respectively. The posterior means of phenotypic correlations of parameter A with IA and IW were estimated as 0.93 and 0.51, respectively. The obtained positive correlations between estimated mature weight and inflection age and weight denote that selection for age and weight at the inflection point would improve the mature weight of the Murciano-Granadina goat breed. Ghiasi et al. (2018) reported estimates of 0.98 and 0.68 for genetic and phenotypic correlations between parameter A and IW in the Raeini Cashmere goats, respectively.

Features of posterior means for genetic and phenotypic correlations between parameters B and K were positive and low values of 0.29 and 0.04, respectively. Similarly, Ghiasi et al. (2018) reported that genetic and phenotypic correlations for B-K were positive and low values of 0.11 and 0.13 in the Raeini Cashmere goat breed, respectively. Contrary to our finding, Kheirabadi and Rashidi (2019) reported negative and high estimates of − 0.994 and − 0.834 for genetic and phenotypic correlations between parameters B and K in the Markhoz goat breed, respectively. Also, Magotra et al. (2021) reported estimates of − 0.90 and − 0.49 for genetic and phenotypic correlations between parameters B and K in Beetal goats of India, respectively.

Positive and medium estimates were obtained for posterior means of genetic correlations of B-IA (0.32) and B-IW (0.38). The corresponding estimates of phenotypic correlations were 0.32 for B-IA and 0.33 for B-IW. Ghiasi et al. (2018) reported estimates of 0.69 and 0.42 for phenotypic correlations of B-IA and B-IW in the Raeini Cashmere goats, respectively. They also reported estimates of 0.73 and 0.56 for correlations of B-IA and B-IW in this breed, respectively.

In the present study, posterior means for genetic and phenotypic correlation estimates of K with IA were − 0.58 and − 0.17, respectively. The corresponding genetic and phenotypic correlations between K and IW were also negative values of − 0.90 and − 0.36 respectively, which imply that as K increases IA and IW would decrease accordingly. Therefore, the existence of such negative correlations between K with IA and IW would be expected. Similarly, Ghaisi et al. (2018) obtained estimates of − 0.36 and − 0.76 for genetic correlations of K-IA and K-IW in the Raeini Cashmere goat breed, respectively. They also reported values of − 0.15 and − 0.30 for phenotypic correlations of K-IA and K-IW, respectively.

In the present study, IA and IW had moderate and positive genetic (0.50) and phenotypic (0.51) correlations, implying that IA and IW were moderately correlated phenotypically and genetically. Ghiasi et al. (2016) fitted a Logistic model on body weight-age records in Raeini Cashmere goats and estimated high genetic (0.99) and phenotypic (0.68) correlations between IA and IW in this breed.

4. Conclusion

In conclusion, our study compared five non-linear mathematical models for their ability to describe the growth trajectory and conduct a genetic evaluation of growth curve traits in the Murciano-Granadina goat breed. The results showed that the von Bertalanffy model provided the best fit based on the lowest values of AIC and RMSE, as well as consideration of the DW statistics. Therefore, it can be concluded that the von Bertalanffy model is a suitable tool for predicting the live weight of the Murciano-Granadina goat breed from birth to 360 days of age. However, we found low levels of additive genetic variation for all growth curve traits studied, which could be attributed to high phenotypic variance from large non-additive genetic and environmental variations. To achieve the desired shape of the growth curve and develop an efficient breeding strategy in the Murciano-Granadina goat breed, it is essential to focus on improving environmental factors that influence growth curve traits. Our findings highlight the importance of considering non-additive genetic and environmental factors in breeding programs to optimize the growth curve traits of the Murciano-Granadina goat breed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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