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Fitting nonlinear models to the growth of New Zealand White rabbits

Ajuste de modelos não lineares ao crescimento de coelhos da raça nova Zelândia Branca

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Highlights

The model by Santos et al. (2018) exhibited the best fit.
New models should be proposed.
Diets containing cassava leaf meal (CLvF) produced low weight gain.
Diets based on hay from the upper third of cassava roots (HUTCR) performed well.

Abstract

This study aimed to assess nonlinear models fit to the growth of New Zealand White rabbits. Rabbit weight was measured every five days between 35 (weaning) and 75 days old (slaughter), in 64 individuals allocated to eight groups and fed a reference diet (REF), simplified and semi-simplified diets consisting of different combinations of three fiber sources: alfalfa hay (AH), cassava leaf meal (CLM) and hay from the upper third of cassava roots (HUTCR). The Santos, Gompertz, Brody, Logistic, Richards and von Bertallanfy models were investigated to determine the best fit based on the model fitting criteria assessed, in addition to identity testing at 5% significance to assess diet feasibility and their effect on animal nutrition. In general, Santos' model performed best according to the fitting criteria analyzed,

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obtaining the highest adjusted coefficient of determination (R^2_{aj}) and the lowest values for the Akaike (AIC) and Bayesian information criteria (BIC) and asymptotic index (AI). Analysis of the growth curves showed that REF exhibited the best growth performance in relation to the other diets, while largely CLM-based diets performed poorly, with low asymptotic weight estimates of 1815 to 1908 g. The semi-simplified diet based on HUTCR performed satisfactorily in terms of asymptotic weight estimates (2210 g), making it a feasible alternative for rabbit farming.
Key words: Diets. Model selection. Growth curve. Statistical modeling.

Resumo

Objetivou-se ajustar modelos não lineares aplicando-os ao crescimento de coelhos da raça Nova Zelândia branca. Os coelhos tiveram seus pesos mensurados a cada cinco dias, entre 35 (desmame) e 75 dias de idade (abate), sendo 64 animais divididos em oito grupos, alimentados por uma dieta referência (REF) e dietas simplificadas e semi-simplificadas baseadas e compostas por diferentes combinações entre três fontes fibrosas: Feno de Alfafa (FAL), Farinha das Folha de Mandioca (FFM) e Feno do Terço Superior da Rama da Mandioca (FTSRM). No estudo foram ajustados os modelos de Santos, Gompertz, Brody, Logístico, Richards e von Bertallanfy, subsequentemente determinado o modelo de melhor ajuste a partir dos critérios avaliadores de ajuste, sendo também realizado o teste de identidade de curvas ao nível de significância de 5%, para avaliar a influência e a viabilidade das dietas na alimentação dos animais. O modelo de Santos obteve no geral, o melhor desempenho de acordo com os critérios avaliadores de ajuste, apresentando maiores índice de $R^2_{aj.}$ e menores valores referentes a AIC, BIC e IA. Na análise das curvas, a dieta REF, obteve um melhor desempenho de crescimento em comparação as demais, e as dietas baseadas majoritariamente por FFM, obtiveram um desempenho insatisfatório apresentando baixas estimativas para o peso assintótico entre 1815 g e 1908 g. Já a dieta semissimplificada com base em FTSRM, apresentou desempenho satisfatório em relação a estimação do peso assintótico (2210 g), podendo ser uma alternativa viável para a criação de coelhos.
Palavras-chave: Dietas. Seleção de modelos. Curva de crescimento. Modelagem estatística.

Introduction

Regression analysis investigates the relationship between a dependent variable and one or more independent variables to estimate population parameters based on samples. How parameters are arranged in the regression equation determines the linearity or nonlinearity of the model (Panik, 2014; Battes & Wates, 2007).

A regression model is classified as nonlinear if at least one of the partial derivatives of the nonlinear function with respect to the parameters depends on at least one of the model parameters (Archontoulis & Miguez, 2015; Bianco & Spano, 2019).

Growth curves are generally adjusted by nonlinear regression, which enables a large volume of information to be condensed into a small set of parameters that can therefore be biologically interpreted (Silva et al., 2012; Mota et al., 2015).

Among the estimated parameters, α and k are highly relevant in biological interpretations,with the former representing the asymptotic weight of rabbits in grams without seasonal variations, or the final weight in the event that the experiment does not reach adult weight, and the latter corresponding to maturity weight, an indicator of the speed at which the animal approaches α (Freitas, 2005). Interpreting these parameters applied to animal growth reflects the economic aspects of production (Mello et al., 2015; Zardin et al., 2019).

Commercial rabbit farming is closely linked to the study of animal growth, and adequately monitoring productive performance may have a decisive effect on profits (Blasco et al., 2018). In this respect, some studies investigate rabbit growth using nonlinear models (Freitas, 2005; Teleken et al., 2017).

Another concern in cuniculture is the high cost of feed, accounting for 60 to 70% of total expenditures, making it important to assess alternatives to replace conventional ingredients. This is feasible for rabbits because they eat fiber-rich diets, competing less with humans when compared to swine and poultry, whose diets contain more grains (Toledo et al., 2012; Molina et al., 2015).

Alternatives such as banana peel and sweet potato vines (Falcone et al., 2023), passion fruit seeds (A. C. S. Ferreira et al., 2021) and cassava by-products such as leaf meal (CLM) and hay from the upper third of roots (HUTCR) (W. M. Ferreira et al., 2007; Oliveira et al., 2011) have been studied as replacements for conventional products.

As such, this study aimed to fit linear models to the growth of New Zealand White rabbits fed different diets and identify the most suitable model. Additionally, model identity testing was performed for the growth curves to assess the quality and feasibility of the alternative diets in terms of rabbit growth.

Methodology

Data

The data were obtained from research by Machado (2010), who conducted a detailed analysis of the growth of New Zealand White rabbits fed eight different diets. The study was approved by the Animal Ethics Committee of the Federal University of Minas Gerais (CETEA/UFMG) under protocol number 171/08.

The minimum and maximum temperatures during the experiment were 20.8 and 26.7°C, respectively. The cages used were made from galvanized wire mesh and measured 0.30 x 0.60m in an available area of 0.18 m^2. Before the animals' arrival, the facilities were cleaned using a blow torch.

Table 1 describes the nutritional and percentage composition of the experimental diets. The reference diet (REF) was formulated in accordance with De Blas and Mateos (1998), and the simplified and semi-simplified diets were prepared based on these same recommendations or providing at least 2200 kcal/kg of digestible energy, the minimum proposed by De Blas et al. (2002) and W. M. Ferreira and Pereira (2003) that allows rabbits to regulate their daily consumption via the chemostatic mechanism.

Table 1
Nutritional and percentage composition of the experimental diets

Ingredient (%)	REF	SCMA	SSCH	SSAH	SSCM	SSCMA	SSCHLM	PSCMA
Alfalfa hay	37.73	47.0	-	83.7	-	41.0	40.09	47.00
Cassava leaf meal	-	41.8	-	-	78.9	40.0	-	41.78
Hay from the upper third of cassava roots	-	-	70.3	-	-	-	37.28	-
Maize	7.584	-	8.000	5.00	5.00	5.00	5.000	-
Soybean meal	4.184	-	10.00	0.04	6.87	5.525	6.020	-
Wheat bran	25.00	-	-	-	-	-	-	-
Soybean oil	-	5.32	5.961	5.36	4.28	4.811	6.000	5.333
Corn meal	20.000	-	-	-	-	-	-	-
Premix	0.500	0.50	0.50	0.50	0.50	0.50	0.500	0.500
Monoammonium phosphate	0.979	0.57	0.57	0.64	0.43	0.53	0.603	0.572
Table salt	0.500	0.50	0.50	0.50	0.50	0.50	0.500	0.500
Molasses powder	2.000	3.00	3.00	3.00	3.00	3.00	3.000	3.000
Bentonite	1.000	1.00	1.00	1.00	1.00	1.00	1.000	1.000
Limestone	0.544	-	-	0.18	-	-	0.91	-
DL-Methionine	0.011	-	-	-	-	-	-	-
Lysine-HCl	-	0.27	0.13	-	-	-	-	0.281
Phytase	-	-	-	-	-	-	-	0.005
Carbohydrase	-	-	-	-	-	-	-	0.020
Nutritional composition analyzed (NM)								
Nutrient (%)								
Dry matter	91.31	91.1	91.1	91.1	90.1	90.2	90.89	92.45
Crude protein	15.15	17.1	17.4	16.4	17.8	19.6	17.47	18.56
Mineral matter	8.34	9.56	9.04	9.77	7.93	8.62	9.47	10.36
Neutral detergent fiber (NDF)	36.35	32.95	46.53	42.16	31.26	33.71	41.30	33.15
Acid detergent fiber (ADF)	16.46	23.7	27.71	25.52	23.74	23.83	26.67	23.81
ADIN (%ADF)	0.67	1.74	1.62	0.96	2.68	2.24	1.68	1.80
Lignified crude protein (%)	4.58	15.1	16.1	9.30	15.7	17.0	15.38	17.13
Hemicellulose (NDF-ADF)	19.89	9.19	18.82	16.64	7.52	9.88	14.63	9.34
ADL	2.7	8.17	8.79	7.05	8.86	8.16	8.78	8.45
Cellulose (NDF-ADF)	13.75	15.59	18.92	18.47	14.88	15.67	17.85	15.36
ADL-to-cellulose ratio	0.20	0.52	0.46	0.38	0.60	0.52	0.49	0.55

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Calcium	0.91	1.40	1.42	1.34	1.09	1.32	1.35	1.37
Phosphorus	0.69	0.47	0.47	0.43	0.38	0.45	0.48	0.42
Metabolizable energy (Kcal/Kg)	3945	4391	4356	4214	4524	4294	4327	4388
Digestible energy	2519	2394	2156	2204	2453	2326	2196	2409

REF: reference diet, **SCMA:** simplified diet based on a mixture of cassava leaf meal and alfalfa hay, **SSCH:** semi-simplified diet based on hay from the upper third of cassava roots (HUTCR), **SSAH:** semi-simplified diet based on alfalfa hay, **SSCM:** semi-simplified diet based on cassava leaf meal, **SSCMA:** semi-simplified diet based on a mixture of cassava leaf meal and alfalfa hay, **SSCHLM:** semi-simplified diet based on a mixture of HUTCR and cassava leaf meal, **PSCMA:** phytase-enriched SCMA diet.

The experiment was conducted in the Animal Metabolism Laboratory of the Animal Science Department at the UFMG Veterinary School. Animals of both sexes were weaned at 35 days old and then distributed into groups. Eight rabbits were used for each diet, totaling 64 animals. The rabbits were fed throughout the experiment and their weight was measured every 5 days until 75 days old (Table 2), when they were slaughtered.

Table 2
Average weight in grams of rabbits in each treatment

Days	REF	SCMA	SSCH	SSAH	SSCM	SSCMA	SSCHLM	PSCMA
35	735.75	722.13	685.14	745.57	762.57	672.50	704.75	714.63
40	847.38	681.75	727.63	786.14	759.43	734.38	745.00	711.88
45	1026.75	839.88	873.00	956.14	865.29	907.88	894.50	834.88
50	1219.88	982.00	1061.50	1144.86	988.71	1077.00	1074.50	979.63
55	1418.25	1132.75	1230.00	1289.29	1088.29	1248.50	1235.88	1116.75
60	1624.75	1280.13	1402.63	1466.43	1215.57	1431.50	1429.38	1258.50
65	1805.13	1432.25	1563.13	1612.71	1339.00	1596.75	1585.13	1396.63
70	1972.88	1608.00	1739.13	1767.57	1494.00	1772.00	1738.00	1552.63
75	2159.75	1754.38	1924.00	1914.86	1623.43	1933.63	1898.13	1682.50

Models

Table 3 presents the models that were fit to the growth data of New Zealand White rabbits, whereα is the asymptotic weight of the animal, that is, when time tends to infinity, β and δ are associated with the shape of the model and have no biological interpretation, K is the maturation rate, which should be interpreted as a change in weight in relation to α, that is, an indicator of the speed at which the animal approaches its adult weight, m the inflection point of the curve, t the weighing time, and ε the experimental error for each observation, which are independent, with normal distribution, a mean of zero and variance of σ^2, the latter being constant.

Table 3
Nonlinear models fit to rabbit growth

Models	Equations
von Bertalanffy (Bertalanffy, 1957)	$Y(t) = \alpha(1-\beta e^{-kt})^3 + \varepsilon$
Gompertz (Laird, 1965)	$Y(t) = \alpha e^{-\beta e^{kt}} + \varepsilon$
Brody (Brody, 1945)	$Y(t) = \alpha\left(1-\beta e^{-kt}\right) + \varepsilon$
Richards (Richards, 1959)	$Y(t) = \alpha\left(1-\beta e^{-kt}\right)^m + \varepsilon$
Logistic (Nelder, 1961)	$Y(t) = \frac{\alpha}{(1+\beta e^{-kt})} + \varepsilon$
Santos (Santos et al., 2018)	$Y(t) = \alpha\left(1-\beta e^{-\delta e^{kt}}\right) + \varepsilon$

Residual analysis and parameter estimation

The assumptions of residuals were checked using the Shapiro-Wilk test (Shapiro & Wilk, 1965) for normality; Durbin-Watson statistic (Durbin & Watson, 1950) for independence and Breusch-Pagan test (Breusch & Pagan, 1979) for homogeneity of variances.

The parameters were estimated by the Gauss-Newton iterative method, using the Nonlinear Least Squares (nls) function of the stats package in R software (R Core Team [R], 2019).

Selection criteria

The following selection criteria were used to determine how well the models fit the growth data:

• Akaike information criterion - (AIC), (Akaike, 1974) determined by

$$AIC = n + n\log(2\pi) + n\log\left(\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}\right) + 2(p+1).$$

• Bayesian information criterion - (BIC), (Schwarz, 1978) given by

$$BIC = n + n\log(2\pi) + n\log\left(\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}\right) + (\log n)(p+1).$$

BIC and AIC balance the goodness-of-fit of a model with its complexity.

• Adjusted coefficient of determination (R_(aj.)^2)

$$R_{aj.}^2 = R^2 - \frac{p-1}{n-p}(1-R^2).$$

Like R^2, the adjusted coefficient of determination ($R^2_{aj.}$) varies between 0 and 1, but adjusts for the number of parameters in the model; the closer the value is to 1, the better the fit.

• Asymptotic Index (AI)

Described by Ratkowsky (1990), the asymptotic index (AI) combines ASE, MAD and R^2 and assigns a weight of 100 to estimates of these criteria. After weighting, it is obtained by the following equation: AI=(ASE+MAD) - R^2. The index was used by Drumond et al. (2013) and Veloso et al. (2016), whereby ASE is the asymptotic standard error, which denotes the square root of the mean square of residuals, calculated by $\sum_{i=1}^{n}(y_i - \hat{y}_i)^2/n - p$ MAD is the mean absolute error, calculated $\sum_{i=1}^{n}|y_i - \hat{y}_i|/n,$ which quantifies the average of absolute differences between actual values and those estimated by the model, and R^2 is the coefficient of determination. In this equation, $\hat{y}_i$ is the expected weight at time *t*, y_i the actual weight at the same time *t*, n sample size, and p the number of parameters. The best-fitting model is that which exhibits the highest R^2_{aj} and lowest AIC, BIC and AI values.

Growth curve model identity

After selecting the model that best fit the diet data, the identity method proposed by Regazzi (2003) was used to determine whether a single curve is capable of depicting rabbit growth for the different diets. Significance was set at 5%.

Results and Discussion

The assumptions of normality, homoscedasticity and independence were met by all the models for each diet at 5% significance (p-valor>0.05), allowing curve fitting without the risk of biased estimates. Exceptions were the Richards and Brody models, which did not fit any of the diet data, the Gompertz model for the SSCM diet, and von Bertalanffy for the SCMA and SSCM diets. According to Fernandes et al. (2014) and Miranda et al. (2021), this analysis is an important step in modeling because violations of any of these assumptions makes the model unreliable in terms of understanding the phenomenon under study.

Table 4 shows the estimated values for the parameters of the models fit to the different diets.4

The von Bertalanffy model produced the highest α estimates, overestimating this parameter for all the diets analyzed. This corroborates the findings of D. S. A. Ferreira et al. (2019), who also found that this parameter was overestimated when analyzing the growth of New Zealand rabbits. The Gompertz and Logistic models also resulted in overestimation of asymptotic weight, with values far above those recorded at the last weighing.

On the other hand, the Santos model did not overestimate asymptotic weight for any of the rabbit diets, producing values similar to those obtained at the last weighing before slaughter. Santos et al. (2018) studied the growth of Santa Inês sheep and observed analogous behavior, with similar estimated and actual values.

In regard to estimates for *k*, which denotes the maturity rate of the rabbits, the lowest estimates for each diet were obtained by the von Bertalanffy model, followed by Gompertz and Logistic, with the highest values recorded by the Santos model.

The models that obtained the highest asymptotes exhibited the lowest maturity rates. These results are consistent with those of Sarmento et al. (2006) and Teixeira et al. (2016), who reported that animals with higher growth rates were less likely to achieve higher maturity weights than those with slower growth in early life.

Table 5 presents the values of the fitting criteria for the growth curves used to model weight in relation to diet. For diets REF, SSAH, SSCMA and SSCH, the Logistic model obtained the highest R^2_{aj} and lowest AIC, BIC and AI values, followed by Santos, Gompertz and von Bertalanffy. However, for the remaining diets, the highest R^2_{aj} and lowest AIC, BIC and AI values were produced by the Santos model.

Table 4
Estimates of the model parameters for the REF, SCMA, SSCH, SSAH, SSCMA, PSCMA and SSCHLM diets

Model	Diet	$\hat{\alpha}$	$\hat{\beta}$	$\hat{k}$	$\hat{\delta}$
Gompertz	REF	4223(454.4)	4.22(0.17)	0.02(0.003)	-
	SCMA	20830(5207)	4.67(2.10)	0.009(0.007)	-
	SSCH	6142(2508)	4.06(0.12)	0.02(0.004)	-
	SSAH	4095(1033)	3.72(0.19)	0.02(0.005)	-
	SSCMA	4595(956)	4.10(0.14)	0.02(0.003)	-
	PSCMA	12220(1818)	4.12(1.16)	0.009(0.006)	-
	SSCHLM	4822(1633)	3.92(0.14)	0.02(0.005)	-
Logistic	REF	3006(117.7)	20.05(0.99)	0.05(0.002)	-
	SCMA	4249(230.9)	18.42(6.44)	0.03(0.007)	-
	SSCH	3234(448.1)	19.08(1.21)	0.04(0.004)	-
	SSAH	2795(287.0)	15.4(1.33)	0.05(0.005)	-
	SSCM	20200(8522)	58.00(24.11)	0.02(0.006)	-
	SSCMA	2917(220.0)	19.52(1.19)	0.05(0.003)	-
	PSCMA	3680(136.8)	15.15(3.39)	0.03(0.006)	-
	SSCHLM	2932(353.9)	17.62(1,42)	0.05(0.005)	-
Santos	REF	2460(150.5)	1.01(0.09)	0.04(0.008	0.08(0.03)
	SCMA	1908(211.5)	0.76(0.11)	0.07(0.02)	0.02(0.01)
	SSCH	2229(288.3)	0.91(0.13)	0.05(0.01)	0.05(0.04)
	SSAH	2105(190.8)	0.90(0.14)	0.05(0.01)	0.06(0.05)
	SSCM	1849(229.7)	0.71(0.10)	0.06(0.02)	0.02(0.01)
	SSCMA	2195(173.5)	0.94(0.10)	0.05(0.01)	0.05(0.03)
	PSCMA	1815(141.6)	0.75(0.09)	0.06(0.02)	0.02(0.01)
	SSCHLM	2040(125.0)	0.85(0.09)	0.06(0.01)	0.03(0.02)
von Bertanlaffy	REF	5568(1069)	0.85(0.03)	0.02(0.003)	
	SSCH	12890(12310)	0.82(0.02)	0.007(0.004)	
	SSAH	5662(2500)	0.78(0.03)	0.01(0.005)	
	SSCMA	7025(2833)	0.83(0.02)	0.01(0.004)	
	PSCMA	19130(17888)	0,90(0.28)	0.002(0.006)	
	SSCHLM	7845(5326)	8,04(0.01)	0.01(0.005)	

Estimate (standard error).

Table 5
Model fitting criteria for the diets

Diet	Model	Fitting Criteria			
		AIC	BIC	$R^2_{aj.}$	AI
REF	Gompertz	83.03	83.81	0.9988	31.35
	Logistic	**78.62**	**79.41**	**0.9992**	**23.91**
	Santos	80.93	81.92	0.9992	25.26
	von Bertalanffy	84.79	85.58	0.9985	34.99
SSAH	Gompertz	91.69	92.47	0.9947	48.23
	Logistic	**90.15**	**90.94**	**0.9955**	**43.62**
	Santos	90.99	91.98	0.9952	45.97
	von Bertalanffy	92.31	93.10	0.9943	50.49
SSCMA	Gompertz	86.81	87.60	0.9973	36.60
	Logistic	**84.22**	**85.00**	**0.9980**	**30.11**
	Santos	84.94	85.92	0.9979	31.90
	von Bertalanffy	87.85	88.64	0.9969	39.54
SSCH	Gompertz	90.84	91.62	0.9956	46.65
	Logistic	**89.51**	**90.30**	**0.9962**	**43.90**
	Santos	90.57	91.55	0.9959	46.99
	von Bertalanffy	91.40	92.19	0.9953	48.41
SCMA	Gompertz	-	-	-	-
	Logistic	97.58	98.35	0.9877	66.48
	Santos	**96.61**	**97.60**	**0.9894**	**60.12**
	von Bertalanffy	-	-	-	-
SSCM	Gompertz	-	-	-	-
	Logistic	89.09	89.87	0.9927	42.18
	Santos	**87.28**	**88.27**	**0.9943**	**33.94**
	von Bertalanffy	-	-	-	-
PSCMA	Gompertz	93.47	94.26	0.9909	55.23
	Logistic	92.76	93.55	0.9916	52.04
	Santos	**90.34**	**91.33**	**0.9938**	**44.14**
	von Bertalanffy	93.72	94.51	0.9906	56.32
SSCHLM	Gompertz	92.73	93.52	0.9943	52.59
	Logistic	90.74	91.53	0.9954	46.04
	Santos	**89.10**	**90.08**	**0.9963**	**42.70**
	von Bertalanffy	93.44	94.23	0.9938	54.98

The difference in determining the best model for each diet depends on the rabbits' acceptance of each treatment, their growth pattern, weight fluctuations, number of weighings per animal, and age at the last weighing (Toral, 2008).

This finding is also reported in other studies on rabbit growth. D. S. A. Ferreira et al. (2019) identified the Logistic model as the most suitable for New Zealand rabbit growth, whereas Teleken et al. (2017) concluded that von Bertalanffy was the best fit for growth data in the same breed.

In the present study, the Santos model was considered the best fit for all the diets, obtaining similar R_aj^2 values for REF, SSAH, SSCMA and SSCH when compared to the Logistic model, and parameter estimates consistent with the growth data under study.

The selection of this recently proposed model highlights the importance of using new models that may produce statistically significant results and more accurate estimates (Brito et al., 2007; Santana et al., 2016).

Considering this model as the best fit, Figure 1 presents the predicted values of the Santos model for rabbit growth in relation to the diets over time.

Based on this model, the identity method was applied, and the null hypothesis rejected ($p<0.05$). As such, there is no evidence to suggest that a single curve can describe rabbit growth for all the diets analyzed.

Given the statistically significant difference between the curves, the diets were compared in pairs to obtain more detailed information on rabbit growth for each diet.

Table 6 presents the model identity values for the conventional REF diet, whereby the growth curve shows no similarity to any of the treatments at 5% significance.

This difference between REF and the other diets was expected because REF contains conventional ingredients such as alfalfa, wheat bran, maize, and soybean meal, exhibiting good digestibility and acceptability values. This corroborates the findings of Coelho et al. (2016), who recorded low digestibility and weight gain for simplified and semi-simplified diets when compared to their conventional counterparts, which contain 30 to 40% bulky sources.

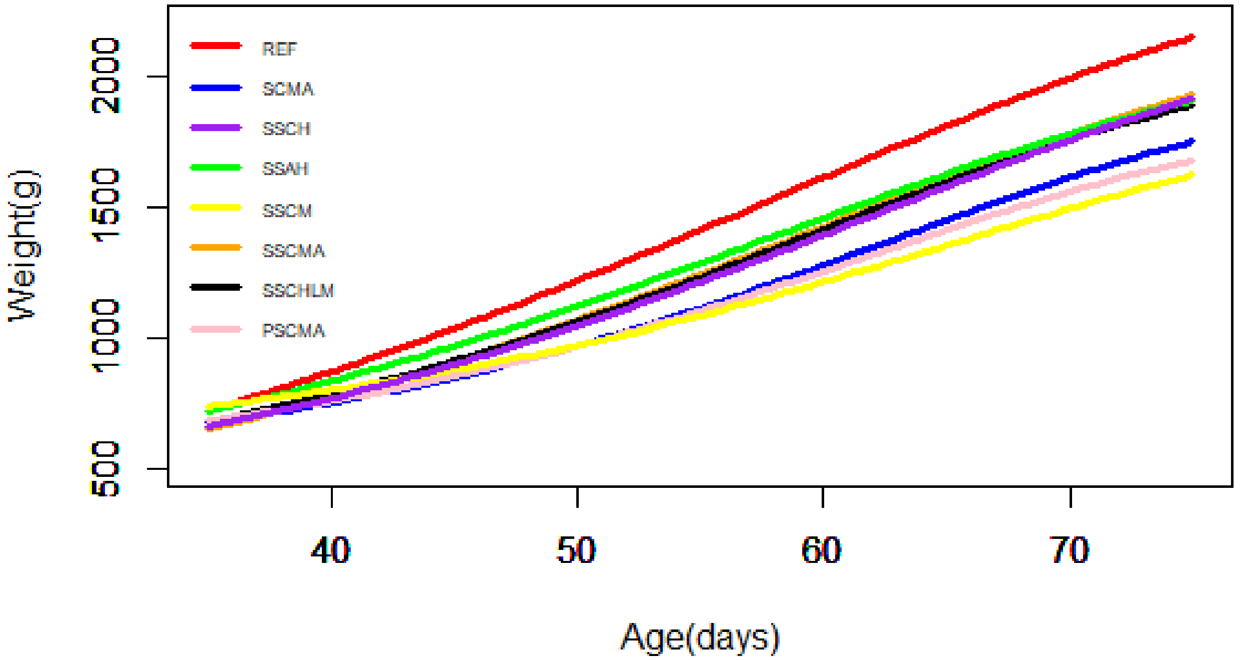

Figure 1. Santos et al. (2018) model fit to the growth of rabbits fed with the REF, SSAH, PSCMA, SSCM, SSCHLM, SCMA, SSCH and SSCMA diets.

Table 6
Model identity test comparing REF with the SSCM, SCMA, SSCH, SSAH, SSCMA, SSCHLM and PSCMA diets

Comparison	Test	SQR_ω	SQR_Ω	v_Ω	v_ω	F_{cal}	p-value
REF and SSCM	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	552729	4219	10	14	325	$1.54\ 10^{-1\ S}$
REF and SCMA	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	385017	9359	10	14	100	$4.99\ 10^{-8\ S}$
REF and SSCH	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	164454	5464	10	14	72.7	$2.36\ 10^{-7\ S}$
REF and SSAH	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	102543	5661	10	14	42.7	$2.94\ 10^{-6\ S}$
REF and SSCMA	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	129463	3571	10	14	88.1	$9.36\ 10^{-8\ S}$
REF and SSCHLM	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	151205	4851	10	14	75.4	$1.99\ 10^{-7\ S}$
REF and PSCMA	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	459269	5364	10	14	211	$1.29\ 10^{-9\ S}$

S – Significant at 5%, F_{cal} – Test statistic, approximation for F distribution.

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Table 7 presents comparisons between the curves for SCMA, SSCM and PSCMA against those of the remaining diets. In addition to differing statistically from the REF diet, the growth curves for SCMA, SSCM and PSCMA were different from those of the other diets (p-value<0.05), indicating less efficient growth and obtaining low asymptotic weights, despite the high maturity rate. This demonstrates that high precocity does not necessarily mean that animals will reach the ideal weight at slaughter.

This pattern of poor performance is likely because these diets contain a high volume of cassava leaf meal (78.94% in SSCM, 40.78% in SCMA, and 41.789% in PSCMA), whose antinutritional properties influence digestibility, such as the presence of polyphenols (tannins), which affect protein use (Corrêa et al., 2004).

These curve comparison tests produced three distinct groups, with REF as the best-performing diet, SSCH, SCHLM, SSAH, and SSCMA exhibiting intermediate performance, and SSCM, SCMA and PSCMA poor performance.

Table 7
Model identity test comparing SCMA, SSCM, and PSCMA with SSCH, SSCHLM, SSCMA and SSCHLM

Comparison	Test	SQR_ω	SQR_Ω	v_Ω	v_ω	F_{cal}	p-value
SCMA and SSCH	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	60307	12033	10	14	10.03	0.002 S
SCMA and SSAH	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	108675	12231	10	14	19.71	$9.8\ 10^{-5}$ S
SCMA and SSCMA	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	79658	10141	10	14	17.14	$1.8\ 10^{-5}$ S
SCMA and SSCHLM	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	65167	11421	10	14	11.77	$8.47\ 10^{-4}$ S
SSCM and SSCH	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	140540	6893	10	14	48.47	$1.63\ 10^{-6}$ S
SSCM and SSAH	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	192711	7091	10	14	65.45	$3.92\ 10^{-7}$ S
SSCM and SSCMA	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	170115	5001	10	14	82.54	$1.29\ 10^{-7}$ S
SSCM and SSCHLM	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	143350	6281	10	14	54.56	$9.33\ 10^{-7}$ S
PSCMA and SSCH	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	89684	8038	10	14	25.39	$3.21\ 10^{-5}$ S
PSCMA and SSAH	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	142151	8236	10	14	40.65	$3.72\ 10^{-6}$ S
PSCMA and SSCMA	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	113638	6146	10	14	43.72	$2.65\ 10^{-6}$ S
PSCMA and SSCHLM	$\alpha_j = \beta_j = \delta_j = k_j \ vs \ H_a$	93887	7425	10	14	29.11	$1.73\ 10^{-5}$ S

S – Significant at 5%, F_{cal} – Test statistic, approximation for F distribution.

Table 8 shows additional identity tests for paired comparisons of the diets analyzed. These indicate that a same curve can depict rabbit growth for both diets (5% significance). The identical curves correspond to intermediate and poorly performing diets.

Table 8
Curves of the diets with identical growth

Comparison	Test	SQR_ω	SQR_Ω	v_Ω	v_ω	F_{cal}	p-value
SCMA and PSCMA	$\alpha_j = \beta_j = \delta_j = k_j \; vs \; H_a$	17091	11934	10	14	1.08	0.416^{NS}
SSCH and SSCMA	$\alpha_j = \beta_j = \delta_j = k_j \; vs \; H_a$	8436.7	6245.4	10	14	0.88	0.511^{NS}
SSCH and SSCHLM	$\alpha_j = \beta_j = \delta_j = k_j \; vs \; H_a$	9000.9	7525.0	10	14	0.49	0.743^{NS}
SSAH and SSFCMA	$\alpha_j = \beta_j = \delta_j = k_j \; vs \; H_a$	15401.3	6442.8	10	14	3.48	0.051^{NS}
SSAH and SSCHLM	$\alpha_j = \beta_j = \delta_j = k_j \; vs \; H_a$	16631.6	7722.3	10	14	2.88	0.079^{NS}
SSCM and PSCMA	$\alpha_j = \beta_j = \delta_j = k_j \; vs \; H_a$	15901.3	6793.9	10	14	3.35	0.055^{NS}
SSCMA and SSCHLM	$\alpha_j = \beta_j = \delta_j = k_j \; vs \; H_a$	7388,8	5632.8	10	14	0.78	0.563^{NS}

NS – Not significant at 5%, F_{cal} – Test statistic, approximation for F distribution.

Considering these diet pairs, Table 9 shows the estimated values of the parameters for the identical growth curves.

Of the diets with intermediate performance, SSCH and SSCMA performed best, obtaining the highest combined asymptotic weight (2210g), with similar maturity rates when compared to those of the remaining diets in this group.

SSCH is composed mainly of hay from the upper third of cassava roots (HUTCR; 70.32%), and SSCMA of alfalfa hay (41.36%) and cassava leaf meal (40%). The fact that the latter diet performed well despite the relatively high amount of cassava leaf meal, which affected growth quality when compared to the other diets, may be due to the high acceptability of alfalfa hay by rabbits, and because SSCMA is semi-simplified and contains soybean meal, which favors palatability.

Table 9
Parameter estimates for pairs of identical curves

Diet	$\hat{\alpha}$	$\hat{\beta}$	$\hat{k}$	$\hat{\delta}$
SSCH and SSCMA	**2210**	**0.929**	**0.0498**	**0.0490**
SSCH and SSCHLM	2119	0.881	0.0382	0.0537
SSAH and SSCMA	2149	0.924	0.0548	0.0489
SSAH and SSCHLM	2071	0.872	0.0451	0.0538
SSAH and PSCMA	2117	0.849	0.0404	0.0529
SSCMA and SSCHLM	2109	0.893	0.0408	0.0534
SCMA and PSCMA	1861	0.754	0.0181	0.0642
SSCM and PSCMA	1842	0.728	0.0204	0.0613

Scapinello et al. (2000) evaluated the incorporation of HUTCR into rabbit feed and found that 20% HUTCR did not significantly affect growth. As such, the authors suggest that completely replacing alfalfa hay would not affect growth performance. However, Machado et al. (2011) reported up to 60% replacement of alfalfa hay and recommended a maximum of 25% HUTCR in rabbit feed to ensure balanced growth performance. Machado et al. (2012) also concluded that incorporating this component may be an economically viable alternative to traditional diets.

Conclusion

The model by Santos et al. (2018) was adequate at describing rabbit growth and can therefore be used in future research applied to other animals.

Comparison of the growth curves showed that diets containing HUTCR performed satisfactorily when compared to the other alternative products studied, resulting in higher weights at slaughter. On the other hand, diets with cassava leaf meal exhibited worse performance, producing lower weights at slaughter.

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