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Test of Equality of Parameters in Growth Curves of Black Castellana Chickens

Teste de Igualdade de Parâmetros nas Curvas Crescimento de Frangos da Raça Castellana Negra

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ABSTRACT

Growth curves and the understanding of sexual dimorphism provide information for increasing productivity in the poultry industry. The study aims to describe the growth of male and female Castellana Negra chickens using the nonlinear Gompertz model and applying the Likelihood Ratio Test (LRT) to compare model parameters to investigate sexual dimorphism. The data were obtained from an experiment involving male and female Castellana Negra chickens. The Gompertz model was adjusted to the data using the maximum likelihood method, and the LRT was employed to assess the equality of growth curve parameters between sexes. The full Gompertz model, in which parameters varied between males and females, proved to be the most suitable for describing the growth of the animals. Therefore, the Castellana Negra breed presents sexual dimorphism in relation to adult weight, the age at maximum growth rate, and the relative growth rate.

keywords likelihood ratio test, model identity, Gompertz model, sexual dimorphism, slow growing birds

RESUMO

As curvas de crescimento e o entendimento acerca do dimorfismo sexual permite obter informações para aumentar a produtividade na indústria avícola. O objetivo deste estudo é descrever o crescimento de frangos machos e fêmeas da raça Castella Negra por meio do modelo não linear Gompertz e usar teste de razão de verossimilhança (LRT) para comparar os parâmetros do modelo a fim de investigar o dimorfismo sexual. Os dados são de um experimento que envolveu fêmeas e machos da raça Castellana Negra. O modelo Gompertz foi ajustado aos dados pelo método de máxima verossimilhança, O LRT foi utilizado para avaliar a igualdade de parâmetros de curvas de crescimento entre os sexos. O modelo Gompertz completo, onde os parâmetros do modelo variam entre machos e fêmeas foi o mais adequado para descrever o crescimento dos animais. Portanto, a raça Castellana Negra apresenta um dimorfismo sexual em relação ao peso adulto, a idade que o animal atinge o crescimento máximo e taxa relativa ao crescimento.

palavras-chave teste de razão de verossimilhança, identidade de modelos, modelo Gompertz, dimorfismo sexual, aves de crescimento lento

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Introduction

Chicken is one of the most consumed meats per capita in the world, according to the Brazilian Animal Protein Association (Associação Brasileira de Proteína Animal [ABPA], 2023). The protein has become well-established due to its high nutritional value, culinary versatility, and broad cultural acceptance, as it does not face religious restrictions, unlike beef and pork.

Among the forms of production, alternative poultry farming stands out, meeting a market demand in which consumers seek an environmentally friendly and healthier system that aims at animal welfare. Since it is more sustainable, this type of poultry production has become a trend in the global market, being well accepted in the retail sector (Albuquerque et al., 2021; Ximenês, 2020).

Castellana Negra' is a native Spanish breed in danger of extinction, adapted to the alternative production system. This breed is classified as light and slow-growing, being a commercial hybrid of broilers and laying hens (Miguel et al., 2007).

Estimating the parameters of animal growth curves is essential to optimize production, through which it is possible to know the weight of birds at different ages. This is crucial for planning feeding, management, and the best time to slaughter with greater precision (Kim et al., 2013; Narinç et al., 2017; Rossi & Santos, 2014).

Nonlinear models are widely used to describe growth curves and have been applied in several studies (Faraji-Arough et al., 2019; González-Ariza et al., 2019; Hoang et al., 2021). According to Narinç et al. (2017), the Gompertz model, is one of the most widely applied to poultry growth.

Although studies show the existence of sexual dimorphism linked to poultry growth, that is, patterns vary according to sex, this finding is usually based on the analysis of parameter estimates, as in the studies by Galán et al., 2023 and González-Ariza et al., 2021).

However, the ideal is to perform some statistical test to verify whether these differences are statistically significant or attributed to chance (Burnham & Anderson, 2002; Pinheiro & Bates, 2000).The likelihood ratio test (LRT) compares parameters of different models in order to verify whether there are significant differences between them, which has been used in several studies (Amaral et al., 2024; Mello et al., 2015; Zardin et al., 2019).

Therefore, the aim of this study was to describe the growth of male and female 'Castellana Negra' chickens using the nonlinear Gompertz model and to use the likelihood ratio test (LRT) to compare the model parameters in order to investigate the existence or not of sexual dimorphism.

Materials and methods

Data to be analyzed correspond to averages taken from the study by Miguel et al. (2007). A total of 994 female and 500 male 'Castellana Negra' chickens were submitted to the experiment. Sex was determined at 4 weeks of age, and from then on, there was a differentiation in the management between sexes. Males were raised in total confinement inside sheds, where confinement spaces measured 13 m^2 each. Females, after reaching 6 weeks of age, were released to external areas, where they could move freely.

Feeding was an important point in the management of animals. From birth (incubation), commercial growth feed was provided *ad libitum*, i.e., animals had unlimited access to the feed. The feed composition included: 12.08 MJ of metabolizable energy and 190 g of crude protein per kg of feed. The average body weight of females and males was measured separately every two weeks, from 4 weeks to 20 weeks of age.

Methodology

The nonlinear Gompertz model, parameterized as described by Fernandes et al. (2015), was adjusted to the average weight data of 'Castellana Negra' chickens using the maximum likelihood method, differentiating sexes, and is expressed as:

$$Y_i = Ae^{-e^{K(B-x_i)}} + \varepsilon_i, \quad (1)$$

where Y_i is the i-th observation of the mean body weight of birds in grams (g), as a function of age, with $i = 4, 6, 8, 10, 12, 14, 16, 18, 20$ weeks. Parameter A represents the horizontal asymptote of the curve, while B corresponds to the abscissa of the inflection point. Parameter K is an index associated with the growth rate,

x_i represents the age of the animal given in weeks, and constant e refers to the base of the natural logarithm, approximately equal to 2.718.

The term ε_i represents the random error associated with the i-th observation. It is assumed that the errors are independent, homoscedastic, and identically distributed, that is, $\varepsilon_i \sim \mathcal{N}(0, \sigma^2)$. This assumption is common in regression models to ensure efficient and unbiased parameter estimators, in addition to enabling the application of statistical inferences, such as hypothesis testing and construction of confidence intervals (Draper & Smith, 1998).

After the initial adjustments, performed using the maximum likelihood method, the determination coefficient (R^2) was calculated for the model adjusted to male and female data, which is a metric that evaluates the quality of the adjustment of a statistical model to the observed data. The closer to 1 or 100%, the better the fit of the model to the data. In addition, a graph comparing the observed and predicted values was also constructed to visually verify the model adequacy.

A residual vector analysis was performed to verify the assumptions of normality (Shapiro-Wilk test), constant variance (Breusch-Pagan), and independence (Durbin-Watson).

The maximum likelihood ratio test was subsequently applied in the context of nonlinear models, as described by Regazzi (2003), which aims to test the equality of parameters between two models. The equality of parameters of the Gompertz model adjusted to male and female birds was tested.

Parameter comparison hypotheses

The aim is to test the equality of parameters A, B and K between groups (males and females) using the likelihood ratio test and to verify whether the inclusion of different parameters for each group significantly improves the model's fit.

The hypotheses tested for A (adult weight) were:

$$\begin{cases} H_0 : A_{\text{male}} = A_{\text{female}} \\ H_1 : A_{\text{male}} \neq A_{\text{female}} \end{cases} \tag{2}$$

The hypotheses tested for B (abscissa of the inflection point) were:

$$\begin{cases} H_0 : B_{\text{male}} = B_{\text{female}} \\ H_1 : B_{\text{male}} \neq B_{\text{female}} \end{cases} \tag{3}$$

The hypotheses tested for K (parameter related to growth rate) were:

$$\begin{cases} H_0 : K_{\text{male}} = K_{\text{female}} \\ H_1 : K_{\text{male}} \neq K_{\text{female}} \end{cases} \tag{4}$$

Adjusted models

For each parameter A, B, and K, described in equations (2)–(4), two models are adjusted: a full model (unrestricted, in which the parameter varies between males and females) and a restricted model (where the parameter is the same for both sexes).

Example: Comparison of parameter A

Full model: Assume that A can be different for males (A_m) and females (A_f), as shown in equation (5):

$$Y_i = \begin{cases} A_m e^{-e^{K(B-x_i)}} + \varepsilon_i, & \text{if the observation belongs to the male group} \\ A_f e^{-e^{K(B-x_i)}} + \varepsilon_i, & \text{if the observation belongs to the female group} \end{cases} \tag{5}$$

where parameter A varies between groups, while B and K are kept constant for both.

Restricted model: Parameter A is assumed to be the same for males and females, as in equation (1), while B and K remain constant.

Maximum likelihood estimation

The parameters of the general Gompertz model, equation (1), the complete Gompertz model, equation (5), and the restricted Gompertz model are adjusted by maximum likelihood, which involves finding the values of parameters A, B, and K that maximize the log-likelihood of the observed data. The log-likelihood function follows the standard formulation described in Casella and Berger (2002) and can be expressed as:

$$\log L(\boldsymbol{\theta}) = \sum_{i=1}^{n} \log f(Y_i \mid \boldsymbol{\theta}). \tag{6}$$

In equation (6), $\boldsymbol{\theta} = (A, B, K)$ are the model parameters, and $f(Y_i \mid \boldsymbol{\theta})$ is the probability density function of Y_i, assumed to follow a normal distribution. After fitting the models, the log-likelihood values $\log L_{\text{restricted}}$ and $\log L_{\text{full}}$ are obtained.

Likelihood ratio test

The likelihood ratio test is used to compare the fit of the restricted and full models. The test statistic is given by:

$$\Lambda = -2\left(\log L_{\text{restricted}} - \log L_{\text{full}}\right). \tag{7}$$

Under the null hypothesis H_0, the statistic Λ in equation (7) follows a chi-square distribution (χ^2), with degrees of freedom equal to the difference in the number of parameters between the models.

For parameter A, there is 1 degree of freedom, since the full model includes one additional parameter (an extra A for the second group). The critical value of the χ^2 distribution is then compared with the value of Λ to determine whether H_0 should be rejected.

If Λ, equation (7), is greater than the critical value of the χ^2 distribution for the chosen significance level (e.g., $\alpha = 0.05$), the null hypothesis H_0 is rejected, indicating that parameter A differs significantly between the groups. Otherwise, H_0 is not rejected, suggesting that there is insufficient evidence to conclude that A differs between males and females.

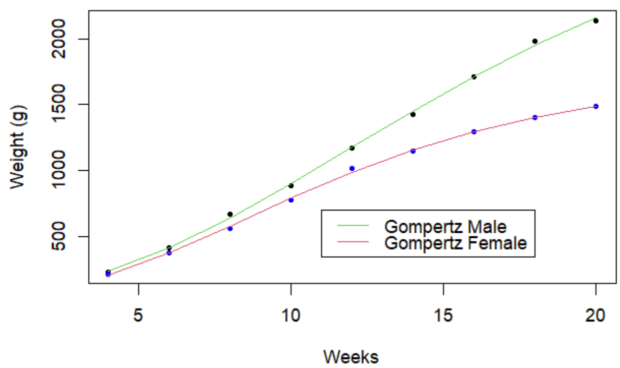
This procedure is repeated for parameters B and K, according to the respective hypotheses tested. For each parameter, full and restricted models were fitted, the statistic Λ was calculated, and comparisons were made using the χ^2 distribution to assess the significance of the differences.

The analyses in this study were performed using the R statistical software (2023, version 4.3.2), with the aid of the `nlme`, `lmtest`, and `tidyverse` packages. For all tests, a nominal significance level of 5% was adopted.

Results and discussion

The nonlinear Gompertz model, described in equation (1), was adjusted to the weight growth data in grams (g) obtained over time in weeks for ‘Castellana Negra’ chickens, separately for each sex. The results of the model fitting are presented in Figure 1.

Figure 1 - Description of the growth curve for the nonlinear Gompertz model adjusted to the average weight data in (g) measured over the weeks for male and female ‘Castellana Negra’ chickens.



The coefficient of determination, R^2, calculated based on the adjusted values obtained by maximum likelihood, was:

$$R^2_{\text{female}} = 99.91\%, \quad R^2_{\text{male}} = 99.90\%. \tag{8}$$

These values show that the model adjusted well to the data, since R^2 was very close to 100%. Furthermore, in Figure 1, which presents the experimentally observed values, referring to the growth of 'Castellana Negra' chickens and the values estimated by the nonlinear Gompertz model, it is possible to observe that the Gompertz model adjusted well to the observed data. This model has been used in literature to describe the growth of birds by authors such as Hoang et al. (2021), Rizzi et al. (2013), and Zhao et al. (2015).

Figure 1 also suggests the presence of sexual dimorphism in relation to the horizontal asymptote. In addition, it was observed that the inflection points for males and females are very close. Although several studies have demonstrated the existence of sexual dimorphism in bird growth, in most cases, statistical tests that verify the significance of this effect are not applied. Generally, the approach is limited to the pointwise analysis of parameter estimates, as observed in the works of González-Ariza et al. (2021) and Galán et al. (2023).

However, to verify whether such visual findings are statistically significant, it is necessary to perform formal statistical tests, such as the maximum likelihood ratio test, to compare model parameters. The parameter estimates of the Gompertz model, applied to the growth data of 'Castellana Negra' chickens for both sexes, are shown in Table 1.

Table 1 - Parameter estimates, with their respective associated confidence intervals (95%), for the Gompertz model applied to the growth data of 'Castellana Negra' chickens for both sexes.

	Female			**Male**		
Parameter	**Estimate**	CI_{Lower}(95%)	CI_{Upper}(95%)	**Estimate**	CI_{Lower}(95%)	CI_{Upper}(95%)
A	1722.7100	1650.0600	1795.3600	3143.0276	2838.5500	3447.5000
B	8.5200	8.1900	8.8400	11.8599	10.9200	12.7900
K	0.1679	0.1539	0.1819	0.1201	0.1060	0.1342

The parameterization used in this work is a strength, since all parameters have direct practical interpretation, according to Fernandes et al. (2015). The parameters of growth functions provide useful information regarding the weight at maturity of animals, such as the maximum reachable weight (A), the age at which the animal reaches maximum growth or abscissa of the inflection point, B, and the relative growth rate (K); in practice, this value indicates how quickly a bird reaches adult size (Narinç et al., 2017).

Table 2 presents the results obtained from the Shapiro-Wilk, Breusch-Pagan, and Durbin-Watson tests, which were applied to assess normality, homoscedasticity, and residual independence, respectively. Due to the unavailability of raw data, all tests were performed based on the residuals obtained from fitting the model to the sample means.

Table 2 - P-values from the Shapiro-Wilk (SW), Durbin-Watson (DW), and Breusch-Pagan (BP) tests applied to the residuals from the Gompertz model for both sexes.

Model Gompertz	**Shapiro-Wilk**	**Durbin-Watson**	**Breusch-Pagan**
Female	0.4288	0.8923	0.5083
Male	0.2833	0.2315	0.6002

*Significant at 5% probability level.

The results of the residual analysis indicate that there is no deviation in the assumptions regarding the residuals, since in the Gompertz model, for each sex, the null hypothesis of normality, homoscedasticity, and residual independence was not rejected. These conditions are essential to ensure reliable estimates of the model parameters and to validate statistical inferences. Considering the context of the chicken population under study, the Gompertz model was able to adequately capture the growth pattern without significant bias.

The results of the maximum likelihood ratio tests performed for all parameters A, B, and K were significant (p-value < 0.05), as shown in Table 3.

Table 3 - Results of likelihood ratio tests using the chi-square statistic: value of the chi-square test ($\chi^2_{\text{cal.}}$), degrees of freedom (D.F.), and p-values.

Hypothesis	$\chi^2_{\text{cal.}}$	D.F.	$P(\chi^2_{(\text{D.F.})} > \chi^2_{\text{cal.}})$
$H_0 : A_{\text{male}} = A_{\text{female}}$	44.468	1	< 0.0001
$H_0 : B_{\text{male}} = B_{\text{female}}$	15.320	1	0.0001
$H_0 : K_{\text{male}} = K_{\text{female}}$	19.801	1	< 0.0001

Thus, it could be concluded that the parameters of the Gompertz model for ‘Castellana Negra’ chickens differ in relation to sex. Studies such as those by Aggrey (2002), Miguel et al. (2007), Galán et al. (2023), and Gonzalez-Ariza et al. (2019), adjusted growth curves separately for males and females and discussed sexual dimorphism in relation to adult weight based on the comparison of the point estimates of the model parameters.

Although punctual estimates provide a central value for parameters, they do not provide information about the uncertainty associated with these estimates. Formal tests such as the likelihood ratio test consider the variability in data and in the estimated parameters, allowing inferring whether the difference found is in fact significant (Casella & Berger, 2002).

In the study by Cajal e Francesch (2014), the general linear model was applied, considering sex as a factor, as well as its interaction, to analyze the weight data of male and female ‘Sobrarbe’ animals, and no significant differences were observed between weights in relation to sex. This breed can be compared to the ‘Castellana Negra’ breed because it is native to Spain, slow-growing and adapted to the alternative farming system, highlighting the need to perform statistical tests to verify sexual dimorphism.

The effect of sexual dimorphism on the body weight of slow-growing chickens is discussed mainly in relation to adult weight. Males are usually significantly heavier than females. Faraji-Arough et al. (2019) reported this difference when comparing the parameters of male and female ‘Khazak’ chickens using the F test. Similarly, Hoang et al. (2021) used analysis of variance to compare the growth pattern of male and female ‘Mia’ chickens.

The adult weight for male and female ‘Castellana Negra’ chickens, represented by parameter A, estimated in this study, Table 1, has values similar to the slow-growing ‘Andalusia Azul’ breed, evaluated in the study by Galan et al. (2023), which found adult weight of 1861.96 g for females and 3000.81 g for males.

Gonzales-Ariza et al. (2019) estimated the maximum weight of 2300 g for males and 1785.80 g for females of the ‘Utrerana’ breed, and Hoang et al. (2021) found maximum weight of 2623.86 g for males and 1770.6 g for females of the ‘Mia’ breed. In both cases, the adult weight of males of the ‘Castellana Negra’ breed estimated in the present study —3143.03 g for males and 1722.71 g for females— is higher than those found, but the adult weight values of females are close.

The estimate of the abscissa of the inflection point for ‘Castellana Negra’ chickens, represented by parameter B, Table 1, was significantly higher for males. Studies involving slow-growing chickens such as that of Mata-Estrada et al. (2020), using the ‘Creole’ breed, reported similar results: the age at inflection was 80.9 days for males and 72.4 days for females. Hoang et al.(2021) also found the abscissa of the inflection point to be 10.5 and 9.86 weeks for males and females, respectively, using the ‘Mia’ breed. In both cases, the estimated values for males are very close to those found in this study, and the values of parameter B for females are higher.

Parameter K, related to the growth rate of ‘Castellana Negra’ chickens, estimated in this study, was significantly higher in females than in males. Parameter K is inversely proportional to parameter A, that is, the higher the A value, the longer the animal takes to reach adult weight, and therefore the K value is lower. The opposite is also true: if the A value is lower, the animal tends to reach its adult weight more quickly, and thus the K value is higher. This behavior can be observed in Table 1 and confirmed by the likelihood ratio test (LRT), in which male chickens have higher weight than females, but parameter K, related to growth rate, is higher in females.

Conclusions

According to the likelihood ratio test, the 'Castellana Negra' breed presents sexual dimorphism in relation to adult weight, the age at which the animal reaches maximum growth, i.e., the abscissa of the inflection point and relative growth rate. The breed follows growth patterns similar to those obtained by other light, slow-growing breeds adapted to the alternative farming system.

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Author contributions

R. de C. Salvador participated in the conceptualization, data curation, formal analysis, methodology, writing – original draft. N. de A. Gonzaga and E. C. P. Azarias participated in the formal analysis. A. A. Pereira and T. J. Fernandes: supervision.

Conflicts of interest

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

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