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Fitting nonlinear models to data from the biquinho pepper plant

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Abstract: *Pepper has several bioactive compounds with antioxidant, anti-inflammatory, and antibacterial properties. Due to its potential, it has several applications in food, industrial and pharmaceutical sectors. The main aim of the research was to fit non-linear growth models to biquinho pepper plant height data. Nonlinear models are important for obtaining information about plant growth that can help at different stages of cultivation. The data were adapted from an experiment carried out in a greenhouse at the Agricultural Engineering Academic Unit (UAEAg), Campus I, of the Federal University of Campina Grande - UFCG. BRS Moema (Capsicum chinense) pepper seeds, developed by the company ISLA Seeds, were used. The sowing recommendations were suggested by the company: depth of 0.5 cm and composition of the soil substrate classified as Eutrophic Gray Clay. The plants were irrigated with* 100% *of their water requirement with wastewater treated by the UASB+ WETLAND sludge blanket up-flow anaerobic reactor. Assessments were carried out every seven days, totaling 21 assessments, 163 days after sowing (DAS), with two plants per replication. The models used in the adjustment were the logistic, Gompertz and von Bertalanffy. The assumptions under residuals of the adjusted models were verified using the Shapiro-Wilk (normality) and Bartlett (homogeneity of variance) tests. Furthermore, models with different variance structures and autoregressive terms were tested. All models evaluated proved to be adequate to adjust to data on the height of the biquinho pepper plant. However, according to the Akaike criterion (AIC), the von Bertalanffy model considering homogeneity of variance without the structure of autoregressive terms presented a better fit. The adjustment estimated an asymptotic plant height of 26.32cm and an inflection point of the curve when it reached approximately 52 days after sowing.*

Keywords: *Regression; Growth models; Pepper cultivation.*

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Introduction

Pepper is a widely used condiments and it is present in several dishes in worlwide cuisine. It has also been used in the pharmaceutical and cosmetics, as well as being used as an ornamental plant. In Brazil, the state of Minas Gerais is the main producer of peppers, followed by São Paulo, Goiás, Ceará and Rio Grande do Sul (Pinto *et al.*, 2023). Cultivation occurs mainly through family farming, being an example of integration between small producers and agribusiness, and therefore there are no exact values for national production. It is estimated that the annual productivity of biquinho pepper represents around 20 t/ha (Ribeiro *et al.*, 2022).

Pepper is from the genus Capsicum belonging to the Solanaceae family and comprises about 43 species, of which five species are domesticated: C. annum, C. baccatum, C. chinense, C. frutescens, and C. pubescens (Barboza *et al.*, 2022; Ribeiro *et al.*, 2020). The C. chinense variety, also known as biquinho pepper, presents high productivity, and uniformity of plants and fruits without pungency with a SHU value - Scoville Heat Units - of zero (Ribeiro *et al.*, 2008). Although its origin is uncertain, there is evidence that its potential dispersal area is the Triângulo Mineiro region, where the largest production of this species is concentrated in Brazil (Ribeiro *et al.*, 2020). Biquinho pepper also contains bioactive compounds such as carotenoids, capsaicinoids, and capsinoids, as well as antioxidant potential (Mariano *et al.* 2022).

Despite some studies with biquinho pepper (Rodrigues *et al.*, 2021; Mangueira *et al.*, 2022; Krause *et al.*, 2023) there is a lack of research on the phenological phases. Phenological studies allow the characterization of the plant development process and support actions, such as fertilization, application of pesticides, transplanting and soil preparation (Rego, Negrelle, Morellato, 2007). In this sense, biological interpretations of parameters can be obtained through nonlinear growth models.

Nonlinear models are used to study growth over time, both in plant and animal areas. The non-linear models most used for these studies are the Logistic, Gompertz, Brody, von Bertalanffy and Richards models.

Several studies with non-linear growth models are reported in the literature. Teixeira *et al.* (2023) described the growth in length and width of pepper and pepper genotypes throughout the crop cycle by comparing four non-linear models (Gompertz, logistic, Richards and von Bertalanffy). Therefore, the Richards model was considered the best for adjusting fruit length, while for width it was the logistic one. Bôas *et al.* (2023) evaluated the growth curves of total dry matter accumulation of hybrids of some corn species using several non-linear models. The authors concluded that the most appropriate models were Gompertz, logistic, von Bertalanffy and Weibull, with the logistic model being the most appropriate to describe the adjustments for the species studied.

Furthermore, the performance of the nonlinear models Gompertz, von Bertalanffy, Brody, Chapman-Richards and Schöngart were adjusted by Campos *et al.* (2022) to describe the height growth of Eucalyptus hybrid clones in a semi-arid region. As a result, they found that Schöngart's model was the best fit for the data. Finally, Mangueira *et al.* (2016) studied corn growth considering different characteristics for the error vector and found that the logistic model with normal asymmetry was the one that presented the best fit to the analyzed data.

Therefore, this work aims to characterize the growth curve of the biquinho pepper plant, using the non-linear models: logistic, Gompertz and von Bertalanffy, adjusting them to plant height data, measured over the days after sowing.

Material and Methods

The experiment was carried out at the Federal University of Campina Grande - UFCG, in the city of Campina Grande, in the state of Paraíba, in a greenhouse belonging to the Agricultural Engineering Academic Unit (UAEAg), Campus I. BRS Moema (Capsicum chinense) pepper seeds, developed by the company ISLA Seeds, were used. The sowing recommendations were suggested by the company: 0.5 cm deep, directly at the cultivation site. For substrate composition, the soil was classified as Eutrophic Gray Clay, collected in the district of São José da Mata in the municipality of Campina Grande - PB, in a 7:3 proportion of soil and tanned cattle manure, 30% of the total volume.

In the treatments, five irrigation depths and two types of water were applied (supply water and wastewater treated by an up-flow anaerobic reactor with sludge blanket - UASB + WETLAND) based on the water needs (NH) of the crop, which are 100% NH, 80% NH, 60% NH, 40% NH and 20% NH.

The data used in the present study refers to the height of plants irrigated with wastewater receiving 100% of their water needs. Assessments were carried out every seven days, totaling 21 assessments, 163 days after sowing (DAS), with two plants per replication. The following models were adjusted to evaluate the growth of the biquinho pepper:

$$\text{logistic: } y_{ij} = \frac{\alpha}{1 + e^{(\gamma - k * x_i)}} + \varepsilon_{ij} \tag{1}$$

$$\text{Gompertz: } y_{ij} = \alpha * e^{-e^{(\gamma - k * x_i)}} + \varepsilon_{ij} \tag{2}$$

$$\text{von Bertalanffy: } y_{ij} = \alpha * (1 - \gamma e^{(-k * x_i)})^3 + \varepsilon_{ij} \tag{3}$$

with y_{ij} representing the height of the ith plant in the jth repetition, x_i representing the ith day after sowing, α being the asymptotic value where growth stabilizes, γ being associated with the inflection point of the curve, k being the maturity rate, that is, it is linked to the speed to reach the asymptotic value and ε_{ij} is the error of the ith observation of the jth repetition. It is assumed that ε_{ij} is independent, has a normal distribution and has a constant variance.

Another parameter evaluated was the inflection point (PI) of the curve. The PI reflects the change in the concavity of the curve, that is, where the studied growth begins to decrease. For the models studied, the PI's are estimated in $(\gamma/k;\ \alpha/2)$, $(\gamma/k;\ \alpha/e)$ and $(log(3\gamma)/k;\ 8\alpha/27)$ for the logistic, Gomperz and von Bertalanffy, respectively.

The assumptions under residuals of the adjusted models were verified using the Shapiro-Wilk (normality) and Bartlett (homogeneity of variance) tests at the 5% level of significance. Furthermore, models with different variance structures and autoregressive terms were tested. The variance structures varIdent and varExp and the autoregressive terms corAR1 were added using the gnls function of the R nmle package. These structures are important when assumptions of variance homogeneity and independence of residuals are not met. To select the most appropriate model for adjustment, the Akaike Information Criterion (AIC) (Akaike, 1974) was used. All data analysis was carried out in the free software R Core Team (2022), using the gnls function of the nmle package.

Result and discussion

The logistic, Gompertz and von Bertalanffy models were verified with and without the structure of autoregressive terms, in addition to the exponential residual variance structure. The logistic models with exponential variance structure, Gompertz with identity variance and von Bertalanffy with identity variance, all without autoregressive term structure, presented better indicators for adjustment. Table 1 shows the estimated parameters of each model mentioned, as well as the AIC values.

According to Table 1, the estimated asymptotic height for the biquinho pepper plant was 25.66 cm, 25.18 cm and 26.32 cm for the logistic, Gompertz and von Bertalanffy models, respectively. The values are higher than those found by Mangueira, Silva and Martins (2022)

Table 1: Estimation of the parameters of each model and the respective AIC.

Models	Parameters				AIC
	α	γ	k	PI	
Logistic	25.66	2.22	0.03	(79.10,12.83)	152.52
Gompertz	25.18	1.34	0.02	(59.02,9.26)	142.55
von Bertalanffy	26.32	0.86	0.02	(51.68,7.80)	138.12

Source: from the authors (2024).

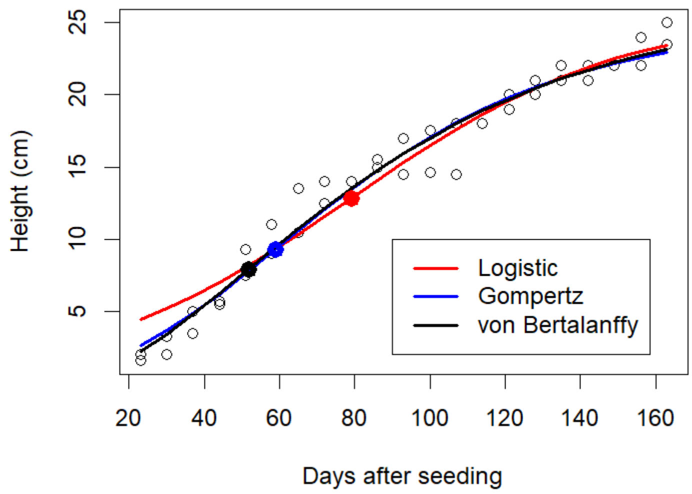
of 7.12, 7.39 and 7.58 cm using the same models, as the authors evaluated the height of plants under water stress, considering only 20% of the plant's water need, which strongly shows the influence of adequate water needs.

In the research carried out by Moreira *et al.* (2021) with biquinho pepper on a bench with reflective material and two types of shading, observed that 70 days after planting, the plant height was less than 20 cm, a value lower than that obtained in this study.

For the inflection point (Table 1), the logistic model estimated a value of approximately 79.10 days. In the Gompertz model, the inflection point of the curve was obtained in 59.02 days and the von Bertalanffy model, the change in concavity of the curve began in approximately 51.68 days after sowing. The logistic model was applied by Diel *et al.* (2020) in two varieties of Biquinho pepper in three growing seasons and found that it was the best growth model.

All models evaluated proved to be suitable for adjusting to a growth curve of the biquinho pepper plant (Figure 1). However, according to the AIC adjustment criterion (Table 1), the most appropriate model was the von Bertalanffy model. Diel *et al.* (2019) also used the logistic, Gompertz and von Bertalanffy models with different parameterizations, however, when adjusting the number and weight of strawberry fruits. The authors concluded that the logistic and Gompertz models were more appropriate according to the measure of intrinsic nonlinearity. Furthermore, the authors conclude that attention should be paid to the Gompertz model, as it may overestimate production and cause disagreements in its interpretation.

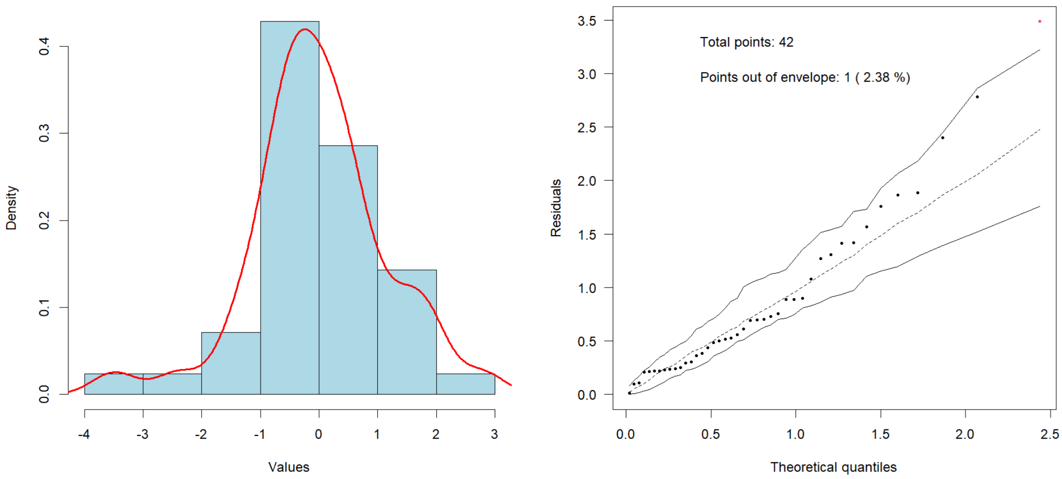
Figure 1: Scatterplot with the fitted models and the inflection point of each curve.



Source: from the authors (2024).

Analyzing the residuals of the von Bertalanffy model regarding their normality, the Shapiro-Wilk test presented a p-value of 0.24, that is, the residuals can be considered to come from a normal distribution. This result is in agreement with the normality graphs presented in Figure 2, which show the histogram with the density curve, in addition to the Quantile-Quantile graph that shows only one point outside the simulated envelope.

Figure 2: Histogram with the density curve of the residuals and quantile-quantile plot with simulated envelope.



Source: from the authors (2024).

Conclusion

The model that had the best fit, according to the AIC, was the von Bertalanffy model. The model considered its adjustment to the homogeneity of residual variance without adjusted autoregressive terms. The adjustment estimated an asymptotic plant height of 26.32cm and an inflection point of the curve when it reached approximately 52 days after sowing, at approximately 7.8 cm in plant height. This indicates that the instantaneous growth rate, that is, the daily growth of the plant, stopped increasing about 52 days after sowing when the plant reached a height of 7.8 cm.

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