UNIVERSIDADE FEDERAL DE SANTA MARIA
CAMPUS FREDERICO WESTPHALEN
PROGRAMA DE PÓS-GRADUAÇÃO EM AGRONOMIA: AGRICULTURA E AMBIENTE

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MODELOS NÃO LINEARES PARA DESCRIÇÃO DO CRESCIMENTO E DESENVOLVIMENTO DE CULTIVARES DE GIRASSOL

Frederico Westphalen, RS
2021

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Dissertação apresentada ao Programa de Pós-Graduação em Agronomia – Agricultura e Ambiente, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para a obtenção do título de **Mestre em Agronomia.**

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Mello, Anderson Chuquel
MODELOS NÃO LINEARES PARA DESCRIÇÃO DO CRESCIMENTO E DESENVOLVIMENTO DE CULTIVARES DE GIRASSOL / Anderson Chuquel Mello.- 2021.
111 p.; 30 cm

Orientador: Marcos Toebe
Coorientador: Volmir Sérgio Marchioro
Dissertação (mestrado) - Universidade Federal de Santa Maria, Campus de Frederico Westphalen, Programa de Pós Graduação em Agronomia - Agricultura e Ambiente, RS, 2021

1. Curva de crescimento 2. *Helianthus annuus* L. 3. heterocedasticidade 4. regressão não linear I. Toebe, Marcos II. Marchioro, Volmir Sérgio III. Título.

Sistema de geração automática de ficha catalográfica da UFSM. Dados fornecidos pelo autor(a). Sob supervisão da Direção da Divisão de Processos Técnicos da Biblioteca Central. Bibliotecária responsável Paula Schoenfeldt Patta CRB 10/1728.

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Aprovado em 16 de Setembro de 2021:
(Defesa de dissertação realizada por Videoconferência)

Marcos Toebe

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Frederico Westphalen, RS
2021

DEDICATÓRIA

Aos meus pais Nivaldo M. Mello e Rosenilda da R. C. Mello;
À minha esposa Thaís V. Mello.

AGRADECIMENTOS

Primeiramente ao meus DEUS, que por meio de seu filho JESUS CRISTO, único e suficiente Senhor e Salvador mudou minha história e acolheu-me em seu plano por meio da graça.

Aos meus pais Nivaldo M. Mello e Rosenilda da R. C. Mello, por serem a base que me sustentou até o presente momento, pelo apoio, amor dedicação e incentivo.

À minha esposa Thaís Vieira Mello, por estar ao meu lado, me apoiando nos momentos de dificuldade e servindo como motivação para continuar.

Aos meus irmãos, tios, tias e demais familiares que não medem esforços para ajudar.

Ao meu orientador Prof. Dr. Marcos Toebe pelo auxílio, oportunidades e acima de tudo pela amizade construída ao longo de seis anos de trabalho iniciados ainda na graduação.

Ao meu coorientador Prof. Dr. Volmir Sergio Marchioro, pelo apoio na realização deste estudo e pela parceria ao ceder o LMGPP para realização das avaliações.

A todos os professores que me oportunizaram aquisição e construção de conhecimento.

Aos colegas dos Grupos de Pesquisa em Estatística e Experimentação Agronômica – GPEEA-Fronteira Oeste e GPEEA-Norte, pelo companheirismo e auxílio.

À Universidade Federal de Santa Maria (UFSM), pela oportunidade de realização do mestrado.

À Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) pela concessão de bolsas de estudo.

À todas as pessoas que, direta ou indiretamente contribuíram para a realização da minha pós-graduação.

“*I'm just a nobody*
Trying to tell everybody
All about Somebody
Who saved my soul.”

Nobody - Casting Crowns

“Seja bendito o nome de Deus de eternidade a eternidade, porque dele são a sabedoria e a força;
E ele muda os tempos e as estações; ele remove os reis e estabelece os reis; ele dá sabedoria aos sábios e conhecimento aos entendidos.
Ele revela o profundo e o escondido; conhece o que está em trevas, e com ele mora a luz.
Ó Deus de meus pais, eu te dou graças e te louvo, porque me deste sabedoria e força;”

Daniel 2:20-23

RESUMO

MODELOS NÃO LINEARES PARA DESCRIÇÃO DO CRESCIMENTO E DESENVOLVIMENTO DE CULTIVARES DE GIRASSOL

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O girassol (*Helianthus annuus* L.) é originário do continente americano e produz óleo de excelente qualidade. A modelagem é uma ferramenta importante para caracterizar o crescimento e o desenvolvimento, pois permite simular o comportamento real de plantas. Portanto, este estudo teve por objetivos aplicar modelos não lineares para a descrição do crescimento e desenvolvimento de três cultivares de girassol; verificar a importância do atendimento dos pressupostos na qualidade do ajuste; utilizar as estimativas dos parâmetros para aplicações práticas e comparações dos padrões de crescimento e desenvolvimento das cultivares; e, definir as coordenadas dos pontos críticos dos modelos que apresentarem melhor ajuste. Os dados utilizados são oriundos de nove ensaios de uniformidade com as cultivares de girassol Aguará 6, Nusol 4510 e Rhino, em três épocas de semeadura, conduzidos na área experimental da Universidade Federal de Santa Maria em Frederico Westphalen – RS/Brasil na safra 2019/2020 e resultaram em três estudos. Os dados de altura de planta (ALT), massa fresca de planta (MFP) e número de folhas (NF) foram ajustados em função da soma térmica acumulada (STa) de 10 plantas coletadas aleatoriamente no ensaio de uniformidade, usando os modelos Logístico (L), Gompertz (G), Brody (B) e von Bertalanffy (VB). Os parâmetros foram estimados por meio do método dos mínimos quadrados ordinários (MQO) ou mínimos quadrados generalizados (MQG). Na presença de violações, utilizou-se o método potência para estruturar a variância. As estimativas dos parâmetros foram comparadas por sobreposição de intervalos de confiança ($IC_{95\%}$) e a qualidade de ajuste dos modelos aos dados foi medida pelo coeficiente de determinação ajustado (R^2_{adj}), critério de informação de Akaike (AIC), critério bayesiano de informação (BIC), e por meio da não linearidade intrínseca (NI) e paramétrica (EP). As análises estatísticas foram realizadas com Microsoft Office Excel® e o software R. No primeiro estudo com a cultivar Rhino os resultados demostraram que os modelos L e G descrevem satisfatoriamente a curva de crescimento em ALT. O modelo L apresenta a melhor qualidade de ajuste, sendo o mais adequado para caracterizar a curva de crescimento. Os pontos críticos estimados fornecem informações importantes para o manejo da cultura. O segundo estudo mostra que a inserção da estrutura potência aos modelos resulta em melhor ajuste de L e G aos dados de MFP. As cultivares Aguará 6 e Nusol 4510 são melhor descritas pelo modelo L, e apresentaram maior fase de crescimento na primeira época. A cultivar Rhino é melhor descrita pelo modelo Gompertz e apresenta redução na fase de crescimento na primeira época. No terceiro estudo, o modelo L foi o mais adequado para descrição do desenvolvimento em NF das cultivares Aguará 6 e Rhino enquanto G é mais adequado para Nusol 4510. O modelo B não deve ser utilizado na descrição do desenvolvimento em NF de cultivares de girassol. Os pontos críticos permitem diferenciar as cultivares de acordo com o padrão de desenvolvimento. Aguará 6 e Rhino atingem o ponto de inflexão (PI) em 50% da assíntota, enquanto Nusol 4510 atinge o PI em 37% da assíntota.

Palavras-chave: Curva de crescimento. *Helianthus annuus* L. Heterocedasticidade. Regressão não linear.

ABSTRACT

NONLINEAR MODELS FOR DESCRIPTION OF GROWTH AND DEVELOPMENT OF SUNFLOWER CULTIVARS

AUTHOR: Anderson Chuquel Mello
ADVISOR: Marcos Toebe

Sunflower (*Helianthus annuus* L.) originates from the American continent and produces excellent quality oil. Modeling is an important tool to characterize growth and development, as it allows simulating the real behavior of plants. Therefore, this study aimed to apply nonlinear models to describe the growth and development of three sunflower cultivars; verify the importance of meeting the assumptions in the quality of the adjustment; use parameter estimates for practical applications and comparisons of cultivar growth and development patterns; and, define the coordinates of the critical points of the models that present the best fit. The data used come from nine uniformity trials with sunflower cultivars Aguará 6, Nusol 4510 and Rhino, in three sowing times, conducted in the experimental area of the Federal University of Santa Maria in Frederico Westphalen – RS/Brazil in the 2019/2020 crop year and resulted in three studies. Plant height (PH), fresh plant mass (FPM) and number of leaves (NL) data were adjusted as a function of the accumulated thermal sum (ATs) of 10 plants randomly collected in the uniformity test, using logistic models (L), Gompertz (G), Brody (B) and von Bertalanffy (VB). The parameters were estimated using the method of ordinary least squares (MQO) or generalized least squares (MQG). In the presence of violations, the power method was used to structure the variance. Parameter estimates were compared by overlapping confidence intervals ($CI_{95\%}$) and the goodness of fit of the models to the data was measured by the adjusted coefficient of determination (R^2_{adj}), Akaike's information criterion (AIC), Bayesian information criterion (BIC), and through intrinsic (IN) and parametric (PE) nonlinearity. Statistical analyzes were performed using Microsoft Office Excel® and R software. In the first study with the cultivar Rhino, the results showed that models L and G satisfactorily describe the growth curve in PH. Model L has the best fit, being the most adequate to characterize the growth curve. The estimated critical points provide important information for managing the crop. The second study shows that the insertion of the power structure into the models results in a better fit of L and G to the FPM data. Cultivars Aguará 6 and Nusol 4510 are better described by model L, and showed the highest growth phase in the first season. Cultivar Rhino is best described by the Gompertz model and shows a reduction in the growth phase in the first season. In the third study, model L was the most suitable for describing the NL development of cultivars Aguará 6 and Rhino while G is more suitable for Nusol 4510. Model B should not be used to describe the NL development of sunflower cultivars. Critical points allow to differentiate cultivars according to the development pattern. Aguará 6 and Rhino reach the inflection point (IP) at 50% of the asymptote, while Nusol 4510 reaches the IP at 37% of the asymptote.

Keywords: Growth curve. *Helianthus annuus* L. Heteroscedasticity. Nonlinear regression.

SUMÁRIO

1. INTRODUÇÃO

O girassol (*Helianthus annuus* L.) é uma eudicotiledonea anual, pertencente à família Asteraceae conhecida mundialmente por produzir aquênios e óleo de altíssima qualidade (Koutroubas et al., 2020). A planta apresenta grande aptidão produtiva, sendo utilizada para fins medicinais, ornamentais, produção de silagem e forragem, adubação verde, biorremediação e produção de biocombustíveis (Amorim et al., 2020; Hesami et al., 2015; Iram et al., 2020).

A cultura é muito adaptável, com potencial de produção em diferentes condições climáticas, classificada como uma das culturas oleaginosas mais importantes do mundo (Kaya, 2020). É a terceira maior em área de produção para extração de óleo, ficando atrás somente da soja [*Glycine max* (L.) Merr.] e da colza (*Brassica napus* L.) (USDA, 2021a). Apesar de ser originária do Continente Norte Americano e domesticada por nativos do Leste dos Estados Unidos, é amplamente cultivada como semente oleaginosa em regiões de climas tropicais e subtropicais de cerca de 72 países (Seiler & Gulya, 2016).

Os países que obtém maiores produtividades estão localizados nos Continentes Europeu e Asiático, sendo Israel o recordista em produtividade, com 5 t ha^{-1}, seguidos por China e Ucrânia, que produzem 2,60 e 2,58 t ha^{-1} respectivamente (USDA, 2021b). O Brasil produz em média 1,6 t ha^{-1}, o que evidencia a necessidade de conhecer a cultura dentro do ambiente no qual está inserida, bem como de investimento em tecnologia para adequação do manejo, visando minimizar esta lacuna de produtividade.

A produção de óleo é o principal fim, pois além do elevado teor (39 a 50%), o óleo de girassol apresenta qualidade superior à outros óleos, devido a maior proporção de ácidos graxos insaturados como oleico, linoleico e linolênico, além de não possuir gorduras trans (Seiler & Gulya, 2016; Castro & Leite, 2018; Kaya, 2020). Além disso, cerca de 10% da produção anual mundial de girassol é destinada para fins não oleosos, sendo esta demanda atendida por genótipos confeiteiros que se caracterizam por terem maior estatura de plantas e sementes maiores, com menores teores de óleo e maiores teores de proteínas (Hladni et al., 2011).

As cultivares atuais são muito diferentes de seus ancestrais primitivos. Os ganhos em produtividade, adaptabilidade e resistência são devidos aos avanços alcançados com inúmeras pesquisas em distintos países. Existem cultivares específicas para cada fim desejado, sendo visível diferenças morfológicas nas plantas em resposta ao potencial genético, ao manejo e ao ambiente de cultivo. Este fato reforça a necessidade de conhecer os padrões de crescimento e desenvolvimento das plantas, o que permite realizar simulações e inferências a respeito do cultivo.

Ainda, a modelagem é uma ferramenta importante para caracterizar o crescimento e o desenvolvimento de plantas, além de, o estudo de curvas de crescimento gerar estratégias para semeaduras futuras, adequando o manejo (Mangueira et al., 2016; Streck et al., 2008).

Modelos matemáticos devem ser capazes de reproduzir o crescimento e desenvolvimento de plantas da forma mais real possível. Os modelos não lineares são os mais utilizados para descrição de curvas de crescimento, sendo mais adequados do que os lineares na descrição de processos biológicos, pois geralmente são mais parcimoniosos e possuem parâmetros com interpretação prática e biológica (Archontoulis & Miguez, 2015; Sousa et al., 2014).

Os modelos são denominados não lineares por questões matemáticas envolvendo suas fórmulas. Modelos lineares permitem a obtenção de seus parâmetros de forma analítica, pois todas as derivadas parciais em relação aos parâmetros do modelo não dependem de nenhum parâmetro. Por outro lado nos modelos não lineares pelo menos uma das derivadas parciais depende de algum parâmetro e não existe transformação capaz de torná-lo linear, sendo necessário uso de métodos iterativos para estimar os parâmetros.

Os parâmetros são estimados pelo método dos mínimos quadrados, por meio de métodos iterativos, que consistem em, a partir de um valor inicial para os parâmetros, inserido pelo pesquisador, ir melhorando-os até que ocorra a convergência para o valor real (Mazucheli & Achcar, 2002). O método de Gauss Newton é amplamente utilizado, sendo também conhecido por método da linearização (Regazzi & Silva, 2010). Este consiste em uma sequência de aproximações de mínimos quadrados lineares para o problema não linear, cada uma das quais é resolvida por um processo “interno” direto ou iterativo (Gratton et al., 2007).

Após a estimação, os resíduos são analisados, geralmente aplicando os testes de Shapiro-Wilk, Durbin-Watson e Breush-Pagan, para a avaliação dos pressupostos de normalidade, independência e homogeneidade de variâncias (homocedasticidade), respectivamente (Muianga et al., 2016). Quando as pressuposições são violadas, os parâmetros devem ser estimados pelo método dos mínimos quadrados generalizados (Mangueira et al., 2016; Muniz et al., 2017).

Nesse caso, é realizada uma ponderação associando-se pesos as observações, fazendo com que as variações tenham menor influência sobre os parâmetros, minimizando o erro padrão das estimativas e as tornando mais confiáveis, através do fornecimento de uma função que descreve o comportamento da variância amostral e de quem ela depende (Fernandes et al., 2014).

De igual modo, a autocorrelação residual pode ser introduzida ao modelo, admitindo-se que os erros são autocorrelacionados na forma de um processo autorregressivo estacionário de ordem p, AR(p). Quando os resíduos são autocorrelacionados as estimativas obtidas podem ser viesadas, com valores abaixo ou acima do verdadeiro valor do parâmetro (Guedes et al., 2004; Mazzini et al., 2005; Pereira et al., 2005).

As funções não lineares mais utilizadas na descrição de curvas de crescimento são as de Richards, Gompertz, von Bertalanffy, Brody e Logística (Mazzini et al., 2003). Alguns destes modelos são sigmoides, ou seja, apresentam curva em formado de “S”, o que os torna mais adequados para descrever curvas de crescimento, pois segundo Mischan & Pinho (2014), o crescimento dos seres vivos apresenta um comportamento distinto, iniciando lentamente, passando para uma fase exponencial e tendendo a estabilizar no final.

Aplicações dos modelos não lineares para descrição de curvas de crescimento e desenvolvimento de plantas, frutos e outros seres vivos estão disponíveis na literatura. Muianga et al. (2016) ajustaram o modelo Logístico com estrutura autorregressiva de primeira ordem na descrição da curva de crescimento de frutos do cajueiro. Frühauf et al. (2021) utilizaram os modelos Brody, Gompertz, Logístico e von Bertalanffy para caracterizar o crescimento diamétrico do cedro (*Cedrela fissilis* Vell.). Outros autores também utilizaram modelos não lineares na descrição do crescimento e desenvolvimento de plantas e frutos como café (Fernandes et al., 2014), cacau (Muniz et al., 2017), crotalária (Bem et al., 2017b), cana de açúcar (Jane et al., 2020).

De acordo com Silva et al. (2021), as curvas de crescimento não apresentam pontos extremos, máximos ou mínimos, mas alguns pontos críticos são importantes, tendo significado específico. Mischan & Pinho (2014), definiram estes pontos para as equações dos modelos Logístico, Gompertz e von Bertalanffy, por meio das derivadas das equações em relação ao tempo. Muitos autores têm utilizado pontos críticos de modelos não lineares na área de ciências agrárias, por estes fornecerem informações relevantes sobre o crescimento de plantas e frutas (Kleinpaul et al., 2019; Carini et al., 2020; Silva et al., 2020; Silva et al., 2021).

Não foram encontradas na literatura aplicações de modelos não lineares para descrição da curva de crescimento e desenvolvimento de girassol. Ainda, observa-se que muitos trabalhos não abordam a necessidade do cumprimento das pressuposições, omitem resultados relevantes para validação dos parâmetros estimados ou não usam métodos de diagnóstico suficientes. Portanto, a aplicação de modelos não lineares para a descrição de curvas de crescimento, bem como de seus pontos críticos, considerando a necessidade de cumprimento das pressuposições proporciona maior conhecimento da cultura dentro do ambiente de cultivo e resulta em adequação do manejo com maior embasamento científico.

2. HIPÓTESES

Modelos não lineares são aplicáveis para a descrição do crescimento e desenvolvimento de cultivares de girassol. Seus parâmetros e pontos críticos fornecem informações práticas para o entendimento e manejo da cultura visando maximizar a produtividade.

3. OBJETIVO GERAL

Caracterizar o crescimento e desenvolvimento de cultivares de girassol, utilizando modelos não lineares.

4. OBJETIVOS ESPECÍFICOS

Selecionar entre os modelos não lineares, o(s) que melhor se ajusta(m) aos caracteres altura, massa fresca de plantas e número de folhas.

Verificar interferência da violação dos pressupostos na qualidade do ajuste;

Comparar os modelos entre cultivares e épocas e fazer inferências sobre os parâmetros estimados;

Utilizar as estimativas dos parâmetros dos modelos com melhor ajuste e com interpretação biológica para aplicação prática no manejo;

Utilizar as estimativas dos pontos críticos dos modelos para inferir sobre o crescimento, desenvolvimento e manejo da cultura.

5. ARTIGO I – NONLINEAR MODELS IN THE HEIGHT DESCRIPTION OF THE RHINO SUNFLOWER CULTIVAR

(Formatação da revista Ciência Rural)

Submetido para o periódico: Ciência Rural

Situação: aprovado em 24.05.21

http://doi.org/10.1590/0103-8478cr20210213

Nonlinear models in the height description of the Rhino sunflower cultivar
Modelos não lineares na descrição de altura da cultivar de girassol Rhino

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5.1 ABSTRACT

Sunflower produces achenes and oil of good quality, besides serving for production of silage, forage and biodiesel. Growth modeling allows knowing the growth pattern of the crop and optimizing the management. The research characterized the growth of the Rhino sunflower cultivar using the Logistic and Gompertz models and to make considerations regarding management based on critical points. The data used come from three uniformity trials with the Rhino confectionery sunflower cultivar carried out in the experimental area of the Federal University of Santa Maria - Campus Frederico Westphalen in the 2019/2020 agricultural harvest. Height was assessed weekly in 10 plants per trial, collected at random. Were realized 14, 12 and 10 assessments for the first, second and third trials, respectively. The data were adjusted for the thermal time accumulated. The parameters were estimated by ordinary least square’s method using the Gauss-Newton algorithm. The fitting quality of the models to the data was measured by the adjusted coefficient of determination, Akaike information criterion, Bayesian information criterion, and through intrinsic and parametric nonlinearity. The inflection points (IP), maximum acceleration (MAP), maximum deceleration (MDP) and asymptotic deceleration (ADP) were determined. Statistical analyses were performed with Microsoft Office Excel® and R software. The models satisfactorily described the height growth curve of sunflower, providing parameters with practical interpretations. The Logistics model has the best fitting quality, being the most suitable for characterizing the growth curve. The estimated critical points provide important information for crop management. Weeds must be controlled until the MAP. Covered fertilizer applications must be carried out between the MAP and IP range. ADP is an indicator of maturity, after reaching this point, the plants can be harvested for the production of silage without loss of volume and quality.

Key words: *Helianthus annuus* L., Logistic, Gompertz, growth curve.

5.2 RESUMO

O girassol produz aquênios e óleo de qualidade, além de servir para produção de silagem, forragem e biodiesel. A modelagem de crescimento permite conhecer o padrão de crescimento da cultura e otimizar o manejo. O objetivo deste trabalho foi caracterizar o crescimento da cultivar de girassol Rhino por meio dos modelos Logístico e Gompertz e fazer considerações a respeito do manejo com base em pontos críticos. Os dados utilizados são oriundos de três ensaios de uniformidade com a cultivar de girassol confeiteiro Rhino, conduzidos na área experimental da Universidade Federal de Santa Maria, Campus Frederico Westphalen, na safra 2019/2020. A altura foi avaliada semanalmente em 10 plantas por ensaio, coletadas aleatoriamente. Foram realizadas 14, 12 e 10 avaliações para o primeiro, segundo e terceiro ensaios, respectivamente. Os dados foram ajustados em função da soma térmica acumulada. Os parâmetros foram estimados por meio do método dos mínimos quadrados ordinários, usando o algoritmo de Gauss-Newton. A qualidade de ajuste dos modelos aos dados foi medida pelo coeficiente de determinação ajustado, critério de informação de Akaike, critério bayesiano de informação, e por meio da não linearidade intrínseca e paramétrica. Foram determinados os pontos de inflexão (IP), máxima aceleração (MAP), máxima desaceleração (MDP) e desaceleração assintótica (ADP). As análises estatísticas foram realizadas com Microsoft Office Excel® e o software R. Os modelos descreveram de forma satisfatória a curva de crescimento da altura do girassol, fornecendo parâmetros com interpretações práticas. O modelo Logístico apresenta melhor qualidade de ajuste, sendo o mais adequado para caracterização da curva de crescimento. Os pontos críticos estimados fornecem informações importantes para o manejo da cultura. As plantas daninhas devem ser controladas até o MAP. As aplicações de fertilizantes em cobertura devem ser realizadas entre MAP e IP. O ADP é um indicador de maturidade, após atingir este ponto, as plantas podem ser colhidas para a produção de silagem sem perda de volume e qualidade.

Palavras-chave: *Helianthus annuus* L., Logístico, Gompertz, curva de crescimento.

5.3 INTRODUCTION

Sunflower (*Helianthus annuus* L.) is an annual broadleaf crop belonging to the Asteraceae family, known worldwide for producing achenes and oil of the highest quality (KOUTROUBAS et al., 2020). This species has a great productive ability, being used for medicinal and ornamental purposes, silage and forage production, green manure, bioremediation, biofuel production, among others (HESAMI et al., 2015; AMORIM et al., 2020; IRAM et al., 2020).

About 10% of the world's annual sunflower production is destined for non-oil purposes, this demand being met by confectionery genotypes that are characterized by having greater stature of larger plants and seeds with lower oil contents and higher protein contents (HLADNI et al., 2011). Height of plants is one of the most important characters for confectionery sunflower genotypes

(PEKCAN et al., 2015; HLADNI et al., 2016), as it correlates with characters such as stem diameter, number of leaves, chapter diameter, seed yield per plant and oil and protein contents (PIVETTA et al., 2012; YANKOV & TAHSIN, 2015).

Low water availability and incidence of pests are responsible for lower productivity and retraction of sunflower's planted area (CONAB, 2020). One way to overcome these difficulties is to seek greater knowledge about how the crop responds to the environment in which it is inserted, aiming at adapting and improving management techniques through growth models. Therefore, modeling becomes an indispensable tool to characterize plant growth and development (STRECK et al., 2008).

Nonlinear models have been used to characterize the growth of many crops such as coffee (FERNANDES et al., 2014), cocoa (MUNIZ et al., 2017), tomato (SARI et al., 2019), sugar cane (JANE et al., 2020), among others. Nonlinear, Logistic and Gompertz models are the most used since they provide a better fit compared to linear models in growth studies and for having parameters with practical and biological interpretation (MAZZINI et al., 2003). Both models have a sigmoidal shape ("S" shape), presenting a slow initial growth, increasing until reaching the so-called inflection point, and decreasing again until reaching its asymptotic limit (MISCHAN & PINHO, 2014).The Logistic model is characterized for being symmetrical in relation to the inflection point, that is, at the inflection point, 50% of the upper asymptote is reached, while in the Gompertz model the inflection point is reached at 37% of the upper asymptote, where there is a change in the concavity of the curve and the growth rate starts to decrease (FERNANDES et al., 2014; JANE et al., 2020).

The critical points in nonlinear models has been used in many studies in agricultural sciences, as it provides relevant information on crop management. In this sense, CARINI et al. (2020), used inflection points, maximum acceleration and maximum deceleration to make inferences about the growth and response of three lettuce cultivars. In turn, KLEINPAUL et al.

(2019), besides using inflection points, maximum acceleration and maximum deceleration, made use of the asymptotic deceleration point to describe the accumulation of fresh and dry rye mass. Therefore, the aim of this study was to characterize the growth of the confectionary sunflower cultivar Rhino by nonlinear Logistic and Gompertz models and to make considerations regarding management based on critical points of the models.

5.4 MATERIALS AND METHODS

During the 2019/2020 agricultural harvest, three uniformity trials (experiments without treatments) were carried out with sunflower in the experimental area of the Federal University of Santa Maria – Frederico Westphalen - RS - Brazil. The area's soil is classified as Red Oxisol and the climate is characterized by Köppen as Cfa (ALVARES et al., 2013). Sowing was performed on September 23, 2019 (First), October 7, 2019 (Second) and October 23, 2019 (Third) using the confectionary sunflower cultivar Rhino, with 0.5 m spacing between rows and 0.33 m between plants.

Sowing was performed manually with two seeds per point and subsequent thinning to obtain the recommended population of 60,000 plants ha^{-1}. Each trial consisted of a strip of 250 m^{2}, containing 10 rows (5 m) per 50 m in length. Fertilization was carried out according to soil analysis and recommendations for the crop (CQFS, 2016), with 10 kg ha^{-1} of N, 70 kg ha^{-1} of K_2O and 60 kg ha^{-1} of P_2O_5 applying at sowing and 50 kg ha^{-1} of N at 30 days after emergence. All cultural treatments were performed uniformly in the experimental area. Height was assessed weekly, destructively on 10 plants per trial, collected at random, with 14, 12 and 10 assessments for the first, second and third trials, respectively.

Height data were adjusted according to the accumulated thermal sum (TSa) after the emergency, calculated according to the method of GILMORE & ROGERS (1958) and ARNOLD

(1959), with a base temperature of 4.2 °C according to determinations made by SENTELHAS et al. (1994). Logistic and Gompertz models were used according to the equations $yi = \frac{a}{1+e^{(b-c*x_i)}} + \varepsilon_i$ and $yi = ae^{[-e^{(b-c*x_i)}]} + \varepsilon_i$, , respectively, where yi represents the observed height values (dependent variable) for i = 1, 2, ..., n observations, and x_i is the ith time measurement of the independent variable (TSa), a represents the asymptotic value of the dependent variable, b is a location parameter, important for maintaining the sigmoidal shape of the model and associated with the abscissa of the inflection point, c is related to the growth rate, the higher the value of parameter c, the shorter the time required to reach the asymptote (a) and ε_i corresponds to the random error, assumed to be independently and identically distributed following a normal distribution with a mean zero and constant variance, that is, $\varepsilon_i \sim N(0,\sigma^2)$.

The parameters were estimated using the ordinary least squares method and the Gauss-Newton algorithm (BATES & WATTS, 1988), implemented in the *nls* ( ) function of the R software. Residue assumptions were verified through the Shapiro-Wilk (SHAPIRO & WILK, 1965), Breusch-Pagan (BREUSCH & PAGAN, 1979) and Durbin-Watson (DURBIN & WATSON, 1950) tests for normality, homogeneity and independence of residues, respectively (RITZ & STREIBIG, 2008). To estimate the parameters, the height data of the trials were used in isolation (First, Second and Third) and later a fourth estimation (All) of the parameters was performed using all three trials in order to observe if model fitting would be better. The confidence intervals of 95% reliability ($CI_{95\%}$) for the parameters were calculated through the difference between 97.5 and 2.5 percentiles of 10,000 bootstrap resamples of model parameters. These upper and lower limits were used to compare the parameters between the trials and models based on the overlapping confidence interval criterion.

The diagnosis of the fitting quality of the model to the data was based on the following criteria: Adjusted coefficient of determination (R^2_{adj}) (SEBER & LEE, 2003), Akaike information criterion (AIC) (AKAIKE, 1974), Bayesian information criterion (BIC)

(SCHWARZ, 1978) and through intrinsic (IN) and parametric (PE) nonlinearity using the Bates and Watts curvature method (BATES & WATTS, 1998). The coordinates of the critical points were obtained using the partial derivatives of the models in relation to the independent variable (TSa). The inflection point (IP), maximum acceleration point (MAP) and deceleration (MDP) and the asymptotic deceleration point (ADP) were determined according to the methodology proposed by MISCHAN et al. (2011). Statistical analyses were performed with Microsoft Office Excel® and R software (R DEVELOPMENT CORE TEAM, 2020).

5.5 RESULTS AND DISCUSSION

The models did not deviate from the normality, homogeneity and independence assumptions, as the values of the Shapiro-Wilk, Durbin-Watson and Breusch-Pagan tests had a statistical p-value>0.05. These results are in agreement with those of CARINI et al. (2020) when using nonlinear models to describe the growth of lettuce cultivars. The Gompertz model stim or greater height asymptotic values (parameter *a*) for the third trial and the fourth situation (All) using all trial, compared to the Logistic model (Table 1). The Logistic model estimates higher *b* values for the second and third trials and the Gompertz model estimates higher values of parameter *b* for the first trial. The *c* values estimated for Logistics were higher in all trials.

When comparing the Logistic model between trials, the estimates of the first and third trials are the same for all parameters, based on the overlapping of confidence intervals (CI), used by WHEELERN et al. (2006), BEM et al. (2017) and CARINI et al. (2020). According to these authors, when at least one parameter estimate is contained within the CI of the other, the difference is not significant. So, the estimated values of 197.357 cm and 202.866 cm for *a*, respectively, in the first and third trials did not differ. The second trial estimates reduced height asymptotic (192.058

cm), but higher values for *b* in relation to the first trial, and higher values for *c* in relation to the first and third trials (Table 1).

Gompertz model estimated different *a* and *b* parameters for all trials (Table 1). The asymptotic height values were 201.088, 195.617 and 213.101 cm, respectively for the first, second and third trial. The *b* parameter differed between the trials, being more variable for the Gompertz model. SARI et al. (2019) used nonlinear models to describe the accumulated tomato production in successive harvests and named *b* as a "scale parameter", associated with the degree of maturation (initial production), however this approach does not apply to sunflower height growth . According to CARINI et al. (2020), the estimate of *b*, in theory, provides a concept of the ratio between the initial values and the amount left to reach the asymptote.

The values of parameter *c*, related to precocity (DIEL et al., 2021), are higher for the second trial for Logistic and Gompertz models. Estimates for *c* parameter are different between the models, higher values are associate to the Logistic (Table 1). The non-difference of *c* between trials can be explained by the use of the same cultivar. The models generated using data from the three trials estimate asymptotic height values of 196.364 cm for Logistics and 200.757 cm for Gompertz, a similar pattern to what we have when the parameters were estimated for the third trial, where the Gompertz values are higher .

Both models fit the data, however the fitting quality estimators used show the Logistic model best described the growth of sunflower plants in height in the four situations studied (Table 1). For all situations, differences between Logistic and Gompertz models were not verified when observing R^2_{adj} in isolation, as the values are similar, varying from 0.963 to 0.972, which shows that both models adjust to all situations, and emphasizes the need for more than one criterion for comparison. The differentiation can be made by observing the other evaluators. The Logistic model presented the lowest values of AIC, BIC, IN and PE for the three trials and also for the fourth situation in which all data are used. Models that present higher values of R^2_{adj} and lower values of

AIC, BIC, IN and PE, should be preferable for growth description (ZEVIANI, 2012; FERNANDES et al., 2014; JANE et al., 2020). The R^2_{adj}, AIC and BIC estimators cannot be compared between trials of the same model because they depended on the number of parameters and observations made (AKAIKE, 1974; SCHWARZ, 1978; SEBER & LEE, 2003), and as already mentioned, both models have three parameters, but 14, 12 and 10 evaluations were performed for the first, second and third trials, respectively. So, the number of observations between trials is unbalanced.

The Logistic model showed a better fit to the data based on the lower values of the AIC, BIC, IN and PE evaluators (Table 1) and on the response of the curves on the data (Figure 1 A-D). Furthermore, the adjustment of Logistics and Gompertz was better when more points were used to estimate the parameters. Also, the Gompertz model underestimated plant height values in the initial period for all situations studied (Figure 1 A-D), being the Logistic model preferable to describe the height growth of the Rhino sunflower cultivar.

As the Logistics model best fits the data, only the critical points generated by this model will be considered. The estimated critical points are shown to be important helpers in crop management. Approximately 21.10% of the asymptote occurs when MAP is reached; 50.00% when IP is reached; 78.80% when MDP is reached; and 90.80% when ADP is reached (MISCHAN & PINHO, 2014). MAP values show plant growth becomes positive and growing from 41.707 cm and 486.545 °C, 40.587 cm and 504.587 °C, 42.871 cm and 542.138 °C accumulated for the first, second and third trials, respectively (Table 1). This indicator is important because in the initial period, before MAP, plants have less growth capacity and, consequently, less ability to compete with spontaneous plants, requiring greater care with weed control up to this point. This observation corroborates studies by BRIGHENTI et al. (2004) and BRIGHENTI (2012), who report that they are necessary for the plant to express all its productive potential, about 30 days after emergence free of weed plants, as they cause growth reduction, chlorosis and decrease in leaf area, stem diameter, chapter and achenes yield.

When IP is reached, the curve changes in the concavity and the growth rate starts to decrease (FERNANDES et al., 2014; JANE et al., 2020). In this study, the height values for the IP were 98.679 cm, 96.029 cm and 101.433 cm with 687.964 °C, 677.780 °C and 749.283 °C accumulated for the first, second and third trials, respectively. According to LOBO et al. (2013), nitrogen and potassium are the nutrients that most limit sunflower production, and from 28 to 56 days after emergence, a period that can be compared to the MAP and IP interval, there is a rapid increase in nutritional demand. Still, VALADÃO et al. (2020), recommend installment applications of boron at 15, 30 and 45 days after sowing, and nitrogen at 30 days after emergence to achieve higher yields. Therefore, fertilizer coverage applications would have optimized results if they were carried out between MAP and IP range

The plant height values observed in the ADP were 179.262 cm, 174.410 cm and 187.237 cm with 1038.632 °C, 979.566 °C and 1109.068 °C accumulated for the first, second and third trials, respectively. According to UCHÔA et al. (2011), the smaller stature of plants is associated with precocity, which gives plants a shorter period of development. Still, the short stature of plants makes it possible to reduce the spacing in future crops, which would assist in the control of weeds (AMABILE et al., 2003). The ADP can be used as a maturity indicator since when reaching this point plants start growth stabilization and can be harvested for producing silage without volume loss and with higher quality, as the flowering phase would be complete (R6 stage), being suitable for silage production (TAN, 2010).

5.6 CONCLUSION

The models show differences between the trials. The Logistic model has a better fit quality, being the most suitable for characterizing the growth curve of the sunflower confectionery cultivar in height. The estimated critical points provide important information for crop management. Weeds must be controlled until the maximum acceleration point. Covered fertilizer applications must be carried out between the maximum acceleration and inflection points. Asymptotic deceleration point is an indicator of maturity, after reaching this point the plants can be harvested for the production of silage without loss of volume and quality.

5.7 DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

5.8 ACKNOWLEDGEMENTS

To the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), to the Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul – FAPERGS and to the Fundação Universidade Federal de Santa Maria – Frederico Westphalen for scholarships. To the FAPERGS/CNPq by financial support (Process number 16/2551-0000257-6 ARD/PPP). To the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brasil, by financial support - Finance code 001.

5.9 AUTHORS’ CONTRIBUTIONS

MT designed and supervised the experiment. ACM, RRS, JCS, VM and ACVP performed the experiments and data collection. ACM performed the statistical analyses. ACM and MT prepared the draft of the manuscript. All authors critically revised the manuscript and approved the final version.

5.10 REFERENCES

AKAIKE, H. A new look at the statistical model identification. **IEEE Transactions on Automatic Control**, v. 19, p. 717-723, 1974. Available from: <https://doi.org/10.1109/TAC.1974.1100705>. Accessed: May. 14, 2021. doi: 10.1109/TAC.1974.1100705

ALVARES, C. A et al. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, v. 22, n. 1, p. 711–728, 2013. Available from: <https://doi.org/10.1127/0941-2948/2013/0507>. Accessed: Mar. 8, 2021. doi: 10.1127/0941-2948/2013/0507

AMABILE, R. F. et al. Growth analysis of sunflower in a Cerrado Oxisol with different levels of basis saturation. **Pesquisa Agropecuária Brasileira**, v. 38, n. 2, p. 219-224, 2003. Available from: <https://doi.org/10.1590/S0100-204X2003000200008>. Accessed: May. 15, 2021. doi: 10.1590/S0100-204X2003000200008

AMORIM, D. S. et al. Fermentation profile and nutritional value of sesame silage compared to usual silages. **Italian Journal of Animal Science**, v. 19, n. 1, p. 230–239, 2020. Available from: <https://doi.org/10.1080/1828051X.2020.1724523>. Accessed: Mar. 5, 2021. doi: 10.1080/1828051X.2020.1724523

ARNOLD, C. T. The determination and significance of the base temperature in a linear heat unit system. **Proceedings of the American Society for Horticultural Science**, v. 74, p. 430-455, 1959.

BATES, D. M.; WATTS, D. G. **Nonlinear regression analysis and its applications**. New York: John Wiley & Sons, 1988.

BATES, D. M.; WATTS, D. G. **Nonlinear regression analysis and its applications**. New York: John Wiley & Sons, 1998.

BEM, C. M. et al. Growth models for morphological traits of sunn hemp. **Semina: Ciências Agrárias**, v. 38, n. 5, p. 2933–2943, 2017. Available from: <https://doi.org/10.5539/jas.v10n1p225>. Accessed: Jan. 5, 2021. doi: 10.5539/jas.v10n1p225

BREUSCH, T.; PAGAN, A. A Simple test for heteroscedasticity and random coefficient variation. **Sociedade Econométrica**, v.47, p. 1287-1294, 1979. Available from: <http://dx.doi.org/10.2307/1911963>. Accessed: May. 14, 2021. doi: 10.2307/1911963

BRIGHENTI, A. M. Resistência do girassol a herbicidas inibidores da enzima acetolactato sintase. **Pesquisa Agropecuária Tropical**, v. 42, n. 2, p. 225–230, 2012. Available from: < https://doi.org/10.1590/S1983-40632012000200014>. Accessed: Jan. 23, 2021 doi: 10.1590/S1983-40632012000200014

BRIGHENTI, A. M. et al. Períodos de interferência de plantas daninhas na cultura do girassol. **Planta Daninha**, v. 22, n. 2, p. 251-257, 2004. Available from: <https://doi.org/10.1590/S0100-83582004000200012>. Accessed: Mar. 16, 2021 doi: 10.1590/S0100-83582004000200012

CARINI, F. et al. Nonlinear models for describing lettuce growth in autumn-winter. **Ciência Rural**, v. 50, n. 7, e20190534, 2020. Available from: <https://dx.doi.org/10.1590/0103-8478cr20190534>. Accessed: Jan. 5, 2021. doi: 10.1590/0103-8478cr20190534

CONAB – Companhia Nacional de Abastecimento. **Acompanhamento da safra brasileira 2019/2020.** Acompanhamento da Safra Brasileira de Grãos 2019/2020, 2020. p. 1–29. Available from: <https://www.conab.gov.br/info-agro/safras/graos>. Accessed: Jan. 1, 2021.

CQFS - Comissão de química e fertilidade do solo. Sociedade Brasileira de Ciência do Solo. **Manual de calagem e adubação para os Estados do Rio Grande do Sul e de Santa Catarina.** Núcleo Regional Sul, 2016, 376p.

DIEL, M. I. et al. Behavior of strawberry production with growth models: A multivariate approach. **Acta Scientiarum - Agronomy,** v. 43, p. 1–11, 2021. Available from: <https://doi.org/10.4025/actasciagron.v43i1.47812>. Accessed: Feb. 4, 2021. doi: 10.4025/actasciagron.v43i1.47812

DURBIN, J.; WATSON, G. S. Testing for serial correlation in least squares regression: I. **Biometrika**, v. 37, n. 3/4, p. 409-428, 1950. Available from: <https://doi.org/10.2307/2332391>. Accessed: May. 14, 2021. doi: 10.2307/2332391

FERNANDES, T. J. et al. Selection of nonlinear models for the description of the growth curves of coffee fruit. **Coffee Science**, v. 9, n. 2, p. 207–215, 2014. Available from: <https://doi.org/10.25186/cs.v9i2.618>. Accessed: Feb. 25, 2021. doi: 10.25186/cs.v9i2.618

GILMORE, E. C.; ROGERS, J. S. Heat units as a method of measuring maturity in corn. **Agronomy Journal**, v. 50, p. 611-615, 1958. Available from: <https://doi.org/10.2134/agronj1958.00021962005000100014x>. Accessed: Jan. 22, 2021. doi: 10.1080/14620316.2018.1472045

HESAMI, S. M. et al. Enhanced biogas production from sunflower stalks using hydrothermal and organosolv pretreatment. **Industrial Crops and Products**, v. 76, p. 449–455, 2015. Available from: <http://dx.doi.org/10.1016/j.indcrop.2015.07.018>. Accessed: Jan. 5, 2021. doi: 10.1016/j.indcrop.2015.07.018

HLADNI, N. et al. Interdependence of yield and yield components of confectionary sunflower hybrids. **Genetika**, v. 43, n. 3, p. 583–594, 2011. Available from: <http://dx.doi.org/10.2298/GENSR1103583H>. Accessed: Mar. 10, 2021. doi: 10.2298/GENSR1103583H

HLADNI, N. et al. Correlation and path analysis of yield and yield components of confectionary sunflower. **Genetika**, v. 48, n. 3, p. 827–835, 2016. Available from: <http://dx.doi.org/10.2298/GENSR1603827H>. Accessed: Mar. 10, 2021. doi: 10.2298/GENSR1603827H

IRAM, S. et al. *Helianthus annuus* based biodiesel production from seed oil garnered from a phytoremediated terrain. **International Journal of Ambient Energy**, v. 41, n. 1, p. 1-9, 2020. Available from: <https://doi.org/10.1080/01430750.2020.1722228 >. Accessed: Feb. 8, 2021. doi: 10.1080/01430750.2020.1722228

JANE, S. A. et al. Adjusting the growth curve of sugarcane varieties using nonlinear models. **Ciência Rural**, v. 50, n. 3, p. 1–10, 2020. Available from: <https://doi.org/10.1590/0103-8478cr20190408>. Accessed: Feb. 8, 2021. doi: 10.1590/0103-8478cr20190408

KLEINPAUL, J. A. et al. Productive traits of rye cultivars grown under different sowing seasons. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 23, n. 12, p. 937–944, 2019. Available from: <http://dx.doi.org/10.1590/1807-1929/agriambi.v23n12p937-944>. Accessed: Mar. 11, 2021. doi: 10.1590/1807-1929/agriambi.v23n12p937-944

KOUTROUBAS, S. D. et al. Sunflower growth and yield response to sewage sludge application under contrasting water availability conditions. **Industrial Crops and Products**, v. 154, p. 112670, 2020. Available from: <https://doi.org/10.1016/j.indcrop.2020.112670>. Accessed: Mar. 11, 2021. doi: 10.1016/j.indcrop.2020.112670

LOBO, T. F. et al. Effect of sewage sludge and nitrogen on production factors of sunflower. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 17, n. 5, p. 504-509, 2013. Available from: < https://doi.org/10.1590/S1415-43662013000500006>. Accessed: May. 17, 2021. doi: 10.1590/S1415-43662013000500006

MAZZINI, A. R. de A. et al. Análise da curva de crescimento de machos Hereford. **Ciência e Agrotecnologia**, v. 27, n. 5, p. 1105–1112, 2003. Available from: <https://doi.org/10.1590/S1413-70542003000500019>. Accessed: Jan. 9, 2021. doi: 10.1590/S1413-70542003000500019

MISCHAN, M. M. et al. Determination of a point sufficiently close to the asymptote in nonlinear growth functions. **Scientia Agricola**, v. 68, p. 109–114, 2011. Available from: <https://doi.org/10.1590/S0103-90162011000100016>. Accessed: Jan. 9, 2021. doi: 10.1590/S0103-90162011000100016

MISCHAN, M. M.; PINHO, S. Z. **Modelos não lineares: funções assintóticas de crescimento**. Cultura Acadêmica: São Paulo, 2014.

MUNIZ, J. A. et al. Nonlinear models for description of cacao fruit growth with assumption violations. **Revista Caatinga**, v. 30, n. 1, p. 250-257, 2017. Available from: <https://doi.org/10.1590/1983-21252017v30n128rc>. Accessed: Mar. 12, 2021. doi: 10.1590/1983-21252017v30n128rc

PEKCAN, V. et al. Developing confectionery sunflower hybrids and determination of their yield performances in different environmental conditions. **Ekin Journal of Crop Breeding and Genetics**, v. 1, n. 2, p. 47–55, 2015. Available from: <https://dergipark.org.tr/tr/pub/ekinjournal/issue/22786/243178>. Accessed: Mar. 12, 2021.

PIVETTA, L. G. et al. Evaluation of sunflower hybrids and the relationship between productive and qualitative parameters. **Revista Ciência Agronômica**, v. 43, n. 3, p. 561–568, 2012. Available from: <https://dx.doi.org/10.1590/S1806-66902012000300020>. Accessed: Mar. 10, 2021. doi: 10.1590/S1806-66902012000300020

R Development Core Team. R: A language and environment for statistical computing. **R Foundation for Statistical Computing**. Vienna, Austria, 2020. Available from <http://www.R-project.org/>. Accessed: Feb. 21, 2021.

RITZ, C.; STREIBIG, J. C. **Nonlinear regression with R**. Springer, New York , 2008. 142p.

SARI, B. G. et al. Nonlinear growth models: An alternative to ANOVA in tomato trials evaluation. **European Journal of Agronomy.** v. 104, p. 21-36, 2019. Available from: <https://doi.org/10.1016/j.eja.2018.12.012> Accessed: Feb. 2, 2021. doi: 10.1016/j.eja.2018.12.012.

SCHWARZ, G. Estimating the Dimension of a Model. **The Annals of Statistics**, v. 6, p, 461-464, 1978. Available from: < http://www.jstor.org/stable/2958889>. Accessed: May. 14, 2021.

SEBER, G. A. F. **Linear Regression Analysis**. New York: John Wiley, 2003. 2ed., 557p.

SENTELHAS, P. C. et al. Base-temperature and degree-days to cultivars of sunflower. **Revista Brasileira de Agrometeorologia**, v. 2, n. 1, p. 43-49, 1994. Available from: <http://www.sbagro.org/files/biblioteca/37.pdf>. Accessed: Feb. 8, 2021.

SHAPIRO, S. S.; WILK, M. B. An analysis of variance test for normality. **Biometrika**, v.52, p.591-611, 1965. Available from: <http://dx.doi.org/10.2307/2333709>. Accessed: May. 14, 2018. doi: 10.2307/2333709

STRECK, N. A. et al. Modeling leaf appearance in cultivated rice and red rice. **Pesquisa Agropecuária Brasileira**, v. 43, p. 559-567, 2008. Available from: <http://dx.doi.org/10.1590/S0100-204X2008000500002>. Accessed: Jan. 20, 2021. doi: S0100-204X2008000500002

TAN, A. S. Sunflower (*Helianthus annuus* L.) researches in the Aegean region of Turkey. **Helia**, v. 33, n. 53, p. 77–84, 2010. Available from: <https://doi.org/10.2298/HEL1053077T> Accessed: Jan. 20, 2021. doi: 10.2298/HEL1053077T

UCHÔA, S. C. P. et al. Potassium fertilization in sidedressing in the yield components of sunflower cultivars. **Revista Ciência Agronômica**, v. 42, n. 1, p. 8-15, 2011. Available from: <https://doi.org/10.1590/S1806-66902011000100002>. Accessed: May. 15, 2021. doi: 10.1590/S1806-66902011000100002

VALADÃO, F. C. A. et al. Sunflower productivity in function of the management of nitrogen fertilization. **Brazilian Journal of Development**, v. 6, n. 11, p. 84197-84213, 2020. Available from: <https://doi.org/10.34117/bjdv6n10-744>. Accessed: May. 17, 2021. doi: 10.34117/bjdv6n10-744

WHEELER, M. W. et al. Comparing median lethal concentration values using confidence interval overlap or ratio tests. **Environmental Toxicology and Chemistry**, v. 25, p. 1441-1444, 2006. Available from: <http://dx.doi.org/10.1897/05-320R.1>. Accessed: Jan. 20, 2021. doi: 10.1897/05-320R.1

YANKOV, B.; TAHSIN, N. Genetic variability and correlation studies in some drought-resistant sunflower (*Helianthus annuus* L.) genotypes. **Journal of Central European Agriculture**, v. 16, n. 2, p. 212–220, 2015. Available from: <http://dx.doi.org/10.5513/JCEA01/16.2.1611>. Accessed: Jan. 21, 2021. doi: 10.5513/JCEA01/16.2.1611

ZEVIANI, W. M. et al. Modelos não lineares para a liberação de potássio de estercos animais em latossolos. **Ciência Rural**, v. 42, n. 10, p. 1789–1796, 2012. Available from: <https://doi.org/10.1590/S0103-84782012001000012>. Accessed: Feb. 21, 2021. doi: 10.1590/S0103-84782012001000012

5.11 TABLE

Table 1. Estimation of parameters *a*, *b* and *c*, lower limit (LL) and upper limit (UL) of the confidence interval ($CI_{95\%}$), Adjusted coefficient of determination (R^2_{adj}), Akaike information criterion (AIC), Bayesian information criterion (BIC), intrinsic curvature measurements (IN), parameter effect curvature measurements (PE), maximum acceleration point (MAP), inflection point (IP), maximum deceleration point (MDP) and asymptotic deceleration point (ADP), of the Logistic and Gompertz models for the trials (First, Second, Third and All) as a function of the accumulated thermal sum (°Cd) of the Rhino sunflower cultivar.

		Logistic				Gompertz			
		First	Second	Third	All	First	Second	Third	All
	LL	194.084	188.080	196.410	193.813	196.824	190.557	203.486	197.443
a	Mean	197.357^{aA}(1)	192.058^{bA}	202.866^{aB}	196.364^{B}	201.088^{bA}	195.617^{cA}	213.101^{aA}	200.757^{A}
	UL	200.718	196.094	209.978	198.936	205.419	200.954	223.804	204.145
	LL	4.137	4.656	4.337	4.504	10.035	2.658	2.289	2.550
b	Mean	4.507^{bB}	5.168^{aA}	4.776^{abA}	4.770^{A}	13.091^{aA}	3.011^{bB}	2.586^{cB}	2.737^{B}
	UL	4.920	5.740	5.266	5.056	17.372	3.417	2.928	2.934
	LL	0.0060	0.0069	0.0057	0.0064	0.0039	0.0045	0.0034	0.0042
c	Mean	0.0066^{bA}	0.0076^{aA}	0.0064^{bA}	0.0068^{A}	0.0043^{bB}	0.0051^{aB}	0.0039^{bB}	0.0045^{B}
	UL	0.0072	0.0085	0.0071	0.0072	0.0048	0.0057	0.0045	0.0048
R^2_{adj}		0.972	0.968	0.967	0.966	0.969	0.963	0.964	0.963
AIC		1111.840	967.070	813.306	2917.444	1131.775	990.471	825.891	2966.234
BIC		1123.606	978.220	823.727	2932.988	1143.541	1001.621	836.312	2981.779
IN		0.069	0.082	0.073	0.045	0.095	0.108	0.103	0.060
PE		0.145	0.172	0.236	0.101	0.203	0.240	0.421	0.143
MAP	x	486.545	504.587	542.138	507.958	368.150	403.643	410.909	394.881
	y	41.707	40.587	42.871	41.494	14.678	14.281	15.557	14.657
IP	x	687.964	677.780	749.283	701.958	590.247	594.189	655.954	609.294
	y	98.679	96.029	101.433	98.176	73.784	71.786	78.202	73.676
MDP	x	889.384	850.972	956.427	895.958	812.423	785.011	900.900	823.708
	y	155.657	151.477	160.002	154.863	137.170	133.491	145.338	136.949
ADP	x	1038.632	979.566	1109.068	1039.638	1005.121	950.126	1113.693	1009.815
	y	179.262	174.410	187.237	178.339	170.247	165.637	180.441	169.998

(1) Comparison of parameter estimates (*a*, *b* and *c*) between trials and between models, based on the overlapping of confidence intervals ($CI_{95\%}$). Averages followed by the same lowercase letter do not differ between trials for the same model. Averages followed by the same capital letter do not differ for the same trial between models.

5.12 FIGURE

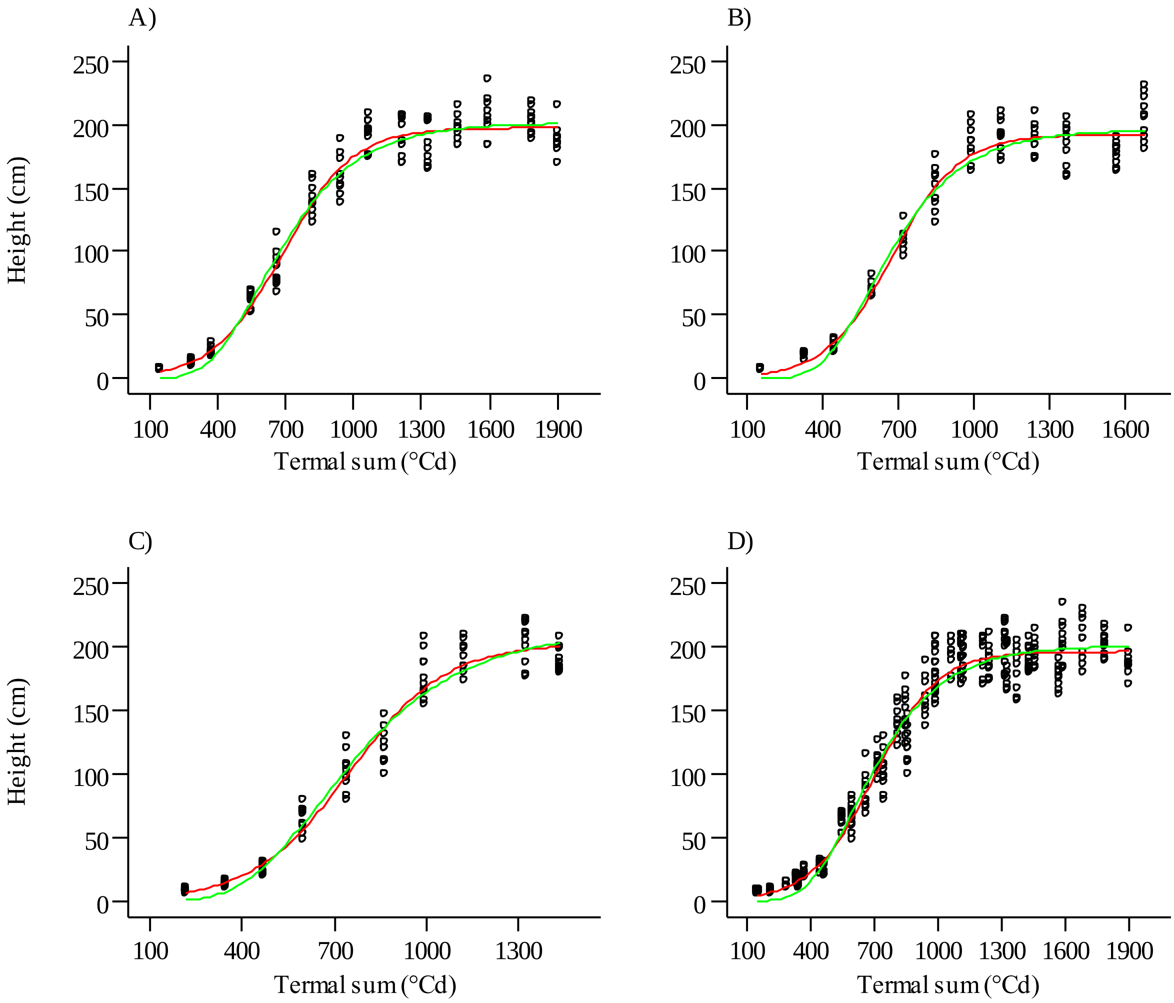

Figure 1. Logistic (red curve) and Gompertz (green curve) models adjusted to the height data of the sunflower cultivar Rhino. A) First trial, B) Second trial, C) Third trial, D) All trials.

6. ARTIGO II – NONLINEAR MODELS IN THE DESCRIPTION OF SUNFLOWER CULTIVARS GROWTH CONSIDERING HETEROSCEDASTICITY

(Formatação da revista Annals of Applied Biology)

Submetido para o periódico: Annals of Applied Biology

Situação: Sob revisão

Nonlinear models in the description of sunflower cultivars growth considering heteroscedasticity

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6.1 ABSTRACT

Plant growth is complex, involves many processes and its understanding is essential to maximize the crops potential. The use of modeling is an essential tool to characterize the plants growth and development, in addition, generates strategies for future plantings, adapting the management. Therefore, this study aimed to apply and make considerations based on parameters of the Logistic and Gompertz models to fresh plants mass, of three sunflower cultivars, sown in three seasons, and select the best model for cultivar. The data used came from nine uniformity trials with the sunflower cultivars Aguará 6, Nusol 4510 and Rhino and were adjusted according to the accumulated growing degree days, using the Logistic and Gompertz models. The parameters were estimated using the methods of ordinary least squares (OLS) and generalized least squares (GLS). In the presence of violations, the power method was used to structure the variance. The fit quality of the models to the data was assessed by adjusted determination coefficient, Akaike information criterion and Schwarz's Bayesian criterion. Logistic and Gompertz models fitted the data, converging on interpretable parameters, both by OLS and GLS methods. The insertion of the power structure to the models resulted in a better fit to the data. The cultivars Aguará 6 and Nusol 4510 are best described by the Logistic model and present higher positive growth phase in the first trial. The sunflower cultivar Rhino is best described by the Gompertz model and present reduction in positive growth phase in the first trial.

Keywords: Growth curve, *Helianthus annuus* L., Heteroscedasticity, Nonlinear regression.

6.2 INTRODUCTION

The sunflower (*Helianthus annuus* L.) is very adaptable, with production potential in different climatic conditions, classified as one of the most important oil crops in the world (Kaya, 2020). It is currently the third largest oil-producing crop, behind only soybeans [*Glycine max* (L.) Merr.] and rapeseed (*Brassica napus* L.) (USDA, 2021a). Despite being originally from the North American continent, the countries that obtain the highest productivity are located in the European and Asian continents, with Israel being the record holder in productivity, with 5 t ha^{-1}, followed by China and Ukraine, which produce 2.60 and 2.58 t ha^{-1} respectively, (USDA, 2021b). Brazil produces 1.6 t ha^{-1}, showing the need to know the culture within the environment in which it is inserted and to invest in technology to adapt the management, aiming to minimize this productivity gap.

The use of modeling is an indispensable tool to characterize the plants growth and development. In addition, the study of growth curves generates strategies for future plantings, adapting the management (Mangueira et al., 2016; Streck et al., 2008). Plant growth is complex, involves many processes and its understanding is essential to maximize the potential of the crops, especially with annual crops of economic importance, expecting to obtain the maximum productive potential. To make this possible, crop management should not be performed based on superficial growth observations but based on models capable of minimizing observations into interpretable parameters and practical use.

Several authors have used nonlinear models to characterize plant growth. Muianga et al. (2016) adjusted the Logistic model with a first-order autoregressive structure in the description of the cashew fruit growth curve. Frühauf et al. (2021) used the Brody, Gompertz, Logistic and Von Bertalanffy models to characterize the diametric growth of cedar (Cedrela fissilis Vell.). Other authors have also used non-linear models to describe the growth of plants and fruits such as coffee (Fernandes et al., 2014), cocoa (Muniz et al., 2017), sunn hemp (Bem et al., 2017b), sugarcane (Jane et al., 2020a), and eucalyptus (Silva et al., 2021).

Nonlinear models are the most used for describing growth curves, being more suitable than linear ones in describing biological processes, as they are generally more parsimonious and have parameters with practical and biological interpretation (Archontoulis and Miguez, 2015; Sousa et al., 2014). The most used nonlinear functions in the description of growth curves are Richards, Gompertz, von Bertalanffy, Brody and Logistic (Mazzini et al., 2003).

Both models used in this study, Logistic and Gompertz, have a sigmoid format (S format). The Logistic model is characterized by being symmetrical concerning the inflection point. That is, at the inflection point 50% of the upper asymptote is reached. On the other hand, in the Gompertz model, the inflection point is reached in 37% of the upper asymptote, in which the curve's concavity changes and the growth rate starts to decrease (Fernandes et al., 2014; Jane et al., 2020a).

The least-squares method is used to estimate the parameters by iterative processes that consist of starting from an initial value for the parameters, inserted by the researcher, improving it until the convergence to the real value occurs (Mazucheli and Achcar, 2002). The Gauss-Newton method is widely used and known as the linearization method (Regazzi and Silva, 2010). It consists of a sequence of linear least-squares approximations for the nonlinear problem, each of them is solved by a direct or iterative “internal” process (Gratton et al., 2007).

After the estimation, the residues are analyzed, generally applying the Shapiro-Wilk, Durbin-Watson and Breusch-Pagan tests, which evaluate the assumptions of normality, residue independence and homogeneity of variance (homoscedasticity), respectively (Muianga et al., 2016). Many studies on growth curves do not consider the need for the assumptions of homogeneity of variances and independence to be met. However, in this type of work, heteroscedasticity among measurements is common, since these are taken over time, and as the plant grows, the variation in its size becomes greater (Fernandes et al., 2014; Mangueira et al., 2016).

The sunflower is strongly influenced by temperature and the accumulated growing degree days being a more accurate measure of biological time than the civil calendar (Gilmore and Rogers, 1958; McMaster and Smika, 1988). Countless studies have calculated the growth curve as a function of the accumulated growing degree days since mathematical models must be able to reproduce the behavior of plants in the most real way possible (Carini et al., 2020).

There are numerous conflicting results regarding the sunflower response to photoperiod, generically cultivars are classified as insensitive, but some may present response (Goyne and Schneiter, 1987; Villalobos et al., 1996; Fonts et al., 2008). However, the cultivation environment directly influences the crop, and the sowing time factor is undisputed in growth, precocity and productivity.

In the literature consulted, no applications of non-linear models were found to describe the growth of the sunflower crop. Therefore, this study aims to apply and make considerations based on parameters of the Logistic and Gompertz models to fresh plants mass of three sunflower cultivars, sown in three seasons, and select the best model for cultivar.

6.3 MATERIAL AND METHODS

6.3.1 Characterization of the experimental design

During the 2019/2020 harvest, nine uniformity trials (blank experiments) were conducted with sunflower (*Helianthus annuus* L.) in the experimental area of the Federal University of Santa Maria - *Campus* Frederico Westphalen - RS - Brazil. The soil in the area is classified as Red Oxisol and the climate is characterized by Köppen as Cfa (Alvares et al., 2013).

Three cultivars were used, one for the production of confectioner grains (Rhino) and two for oil extraction (Nusol 4510 and Aguará 6). Each cultivar was sown on three dates, according to the recommended sowing time. The cultivar Rhino was sown on September 23, 2019 (R1), October 7, 2019 (R2) and October 23, 2019 (R3), the cultivar Nusol on October 23, 2019 (N1), November 6, 2019 (N2) and November 22, 2019 (N3) and the cultivar Aguará 6 on October 23, 2019 (A1), November 6, 2019 (A2) and November 29, 2019 (A3).

Sowing was performed manually with a spacing of 0.5 m between rows and 0.33 m between plants. Two seeds were placed per point with subsequent thinning to obtain the recommended population of 60,000 plants ha^{-1}. Each of the trials consisted of a 250 m^2 strip, containing 10 lines (5 m) per 50 m in length. Fertilization was carried out according to soil analysis and recommendations for culture (CQFS, 2016), with 10 kg ha^{-1} of N, 70 kg ha^{-1} of K_2O and 60 kg ha^{-1} of P_2O_5 at sowing and 50 kg ha^{-1} of N at 30 days after emergence. All cultural treatments were carried out uniformly in the experimental area.

6.3.2 Calculation of accumulated growing degree days

The fresh plant mass data were adjusted according to the accumulated growing degree days (GDD, °C) after the emergency, calculated according to the method of Gilmore & Rogers (1958) and Arnold (1959), with a base temperature of 4.2 °C according to determinations made by Sentelhas et al. (1994). The meteorological data used come from the automated station, located about 500 m from the experimental area with the following geographical coordinates, latitude 27º23'44 ”S and longitude 53º25'46” W and linked to the National Institute of Meteorology (Instituto Nacional de Meteorologia - INMET).

6.3.3 Description of fresh mass accumulation by non-linear models

The Logistic and Gompertz models were used to describe the fresh plant mass accumulation of sunflower plants based on three reasons: (1) the functions produce sigmoid curves, (2) the parameters have biological significance for the accumulation of fresh plant mass, and (3) the models are computationally treatable, that is, the calculations converge in parameter estimates (Meade et al., 2013). The evaluations of fresh plant mass (FPM, g) were carried out weekly, in a destructive way. Ten plants were collected per trial at random, with between nine and 14 evaluations being carried out for each trial. The plants were cut close to the ground, collected and identified in the field and then taken to the laboratory where the FPM evaluation was performed using a precision scale.

In total, 103 evaluations were carried out on 1030 plants from the nine trials. For the generation of the models, nine evaluations were used in each cultivar and trial, since the FPM accumulation had already reached the asymptote and stabilized. The objective was to standardize fit evaluators as they are dependent on the number of parameters and assessments (Akaike, 1974; Seber and Lee , 2003; Schwarz, 1978). The models were generated by five points per evaluation, which were obtained from the average of each two plants sampled, randomly ordered. This procedure was carried out with the objective of normalizing the models' residues, avoiding the data transformation, which would result in the loss of the practical interpretation of the parameters.

The Logistic and Gompertz models were used according to the equations,

$$yi = \frac{a}{1+e^{c*(b-x_i)}} + \varepsilon_i$$

and,

$$yi = ae^{-e^{c*(b-x_i)}} + \varepsilon_i,$$

respectively, where yi represents the observed fresh plant mass values (dependent variable) for i = 1, 2, ..., n observations; x_i is the ith observation of the accumulated growing degree days

(GDD, independent variable); *a* represents the asymptotic value of the dependent variable; *b* is the abscissa of the inflection point; *c* is related with growth, the higher value of parameter *c*, the shorter the time required to reach the asymptote (*a*), and ε_i corresponds to the random error, assumed to be independently and identically distributed following a normal distribution with a mean zero and constant variance, that is, $\varepsilon_i \sim N(0,\sigma^2)$.

6.3.4 Estimation methods and covariance structures

Initially, the parameters were estimated using the Ordinary Least Squares (OLS) method, using the Gauss-Newton algorithm, with the *nls* () function (R Core Team, 2020). To estimate the parameters, the FPM data of the trials (First, Second and Third) were used in isolation for each cultivar and, subsequently, a fourth estimation (All) of the parameters was performed using the average of the three trials with the cultivar, in order to observe whether the fit of the models would be better. The residuals assumptions were verified using the Shapiro-Wilk, Breusch-Pagan and Durbin-Watson tests for normality, homogeneity and independence of the residues, respectively (Ritz and Streibig, 2008). When there was a violation of the assumptions, verified by p-value <0.01, the generalized least squares method (GLS) was used, considering the appropriate variance structures for each model. The models were generated using the *gnls* function available in the *nlme* package (Pinheiro et al., 2020).

In the presence of variances heterogeneity, verified by the Breusch-Pagan test and by the graphical visualization of the residuals and adjusted values, the power method was used to structure the variance matrix. This method allows specifying the variance model and modeling it according to the power of a predictor (Ritz and Streiberg, 2008), in this study being the absolute value of GDD. The structure has the ability to decrease the variance as GDD increases, by adding a variance parameter to the model. The model assumes heteroscedasticity from the power variance function, which is a constructor of the *varPower* class, available in the *nlme* package library (Pinheiro et al., 2020), according to the equation

$$Var(e) = \sigma^2 \mid \upsilon \mid^{2\delta},$$

where e is the random error, σ is the variance, υ is the covariable GDD and δ is a variance parameter that must be $\delta \neq 0$ (Silva et al., 2015).

6.3.5 Methods of diagnostic and comparison

The diagnosis on the quality of the models fit the data was made based on the following criteria: Adjusted coefficient of determination (R^2_{adj}), Akaike information criterion (AIC) and Schwarz's Bayesian criterion (BIC).

R^2_{adj} is used to compare the quality of model fit with different numbers of parameters (p), weighting the coefficient of determination (R^2), the number of explanatory variables in the model (p) and the number of observations (n) in the sample. According to Seber and Lee (2003), its formula is given by:

$$R^2_{adj} = 1 - [\frac{(n-1)}{n-(p-1)}](1 - R^2),$$

where R^2 is the square of the simple linear correlation coefficient between the observed value and the estimated value.

The AIC is given by:

$$AIC = -2 \log L(\hat{\theta}) + 2(p),$$

where: p is the number of parameters and $\log L(\hat{\theta})$ is the logarithm value of the likelihood function evaluated in the estimates of the parameters. AIC lower values reflect a better fit (Akaike, 1974).

The BIC was proposed by Schwarz (1978) and in the same way as the AIC, it takes into account the number of parameters, and the lower the value of the BIC, the better the model will fit (Schwarz, 1978). Its expression is given by

$$BIC = -2\, log\, L(\hat{\theta}) + p.log(n),$$

where n is the number of observations used to adjust the curve and p the number of parameters.

Still, for comparison of the models, confidence intervals were built using the *confint* function of the *stats* package of the R software (R Core Team, 2020). The 95% confidence intervals ($CI_{95\%}$) for the parameters were used to compare the parameters of the best models for each cultivar between trials, based on the criterion of overlapping confidence intervals (CI) according to the methodology used by Wheeler et al. (2006), Bem et al. (2017a) and Carini et al. (2020). According to these authors, when at least one of the parameter estimates is contained within the CI of the other, the difference is not significant.

6.3.6 Software

All statistical analyzes were performed using the R software (R Core Team, 2020). The nonlinear models were adjusted using the *nls* and *gnls* functions, available in the *stats* (R Core Team, 2020) and *nlme* (Pinheiro et al., 2020) packages, respectively. Residue analyzes were performed using the functions *shapiro.test* (R Core Team, 2020), *bptest* and *dwtest* (*lmtest* package, Zeileis and Hothorn, 2002), used for normality, heteroscedasticity and independence, respectively. Confidence intervals were generated using the *confint* function of the *stats* package (R Core Team, 2020). The graphics were built using the *stats* (R Core Team, 2020) and *ggplot2* (Wickham, 2016) packages.

6.4 RESULTS

6.4.1 Error structure analysis

Table 1 shows the results of the Shapiro-Wilk, Durbin-Watson and Breusch-Pagan tests, which evaluate the assumptions of normality, residue independence and variance homogeneity, respectively. Deviations in the normality of the residues are not observed for all models generated, however, in some situations, the assumption of homogeneity of variances were violated considering p-value <0.01.

The cultivar Aguará 6 showed deviation for the assumption of homogeneity of variances for Logistic model in the first, second and third trial, and for Gompertz only in the second trial. In the fourth situation, in which the averages of the three trials were used, there was no violation of the assumptions. The cultivar Nusol 4510 showed violation of variances homogeneity for both models in the second trial. For the Rhino cultivar, only in the first trial are violations of variances homogeneity observed for both models used.

Figure 1 and 2 show the behavior of the standardized residues of the Logistic and Gompertz models, respectively, considering homoscedasticity (Constant model), and heteroscedasticity (Power model). Only graphs of the models that violated the assumptions were created according to Table 1.

Figure 1 shows the standardized residues of the Logistic models for the first (A1), second (A2) and third (A3) trial with the cultivar Aguará, for the second (N2) trial with the cultivar Nusol and for the first (R1) trial with the cultivar Rhino. The initial model, considering constant variance (OLS) presents pattern of residual distribution. Note that the variances increase as thermal time increase, that is, as the plants grow, the variances become larger. As these violations were significant, the standardized residues for the Power model are also shown in the figure, and it is possible to observe that these do not present a pattern as the initial models (Figure 1).

Figure 2 shows the standardized residues of the Gompertz models for the second (A2) trial with the cultivar Aguará, for the second (N2) trial with the cultivar Nusol and also for the first (R1) trial with the cultivar Rhino. Again, a residual pattern is observed for the constant model (OLS) that indicates heteroscedasticity. As these violations are significant, as shown in Table 1, the standardized residues for the Power model are also shown in the figure, making it possible to observe that they do not present a residual distribution pattern (Figure 2).

6.4.2 Models selection and assumptions

Logistic and Gompertz models fit the data, both through the method of ordinary least squares and through the method of generalized least squares. Therefore, the selection of the best model must be made based on the criteria for assessing the quality of fit (Table 4), and on the adjustment of the curves on the data shown in Figures 3 and 4.

Were adjusted 24 models using ordinary least squares (OLS), and eight have violated the assumption of homoscedasticity, being necessary to use the power method and generalized least squares (Table 1). All models adjusted by OLS have R^2_{adj} greater than 0.85, which shows a good fit. The lowest value is observed for the cultivar Nusol 4510 in the first trial, being 0.856 for Gompertz model (Table 4). Even when comparing the models that violate the assumptions and those that assume the violation, there is little or no variation in R^2_{adj}. Therefore, this parameter should not be used in isolation to compare the models in terms of fit, which makes it necessary to observe the other criteria, AIC and BIC.

The results show, that considering the deviation from the homoscedasticity assumption, in addition to being correct because minimizing the standard error, implies in better fit of the models to the data, reducing the evaluators AIC and BIC. Models that consider heteroscedasticity show R^2_{adj} being higher than 0.90 and significant reductions for AIC and BIC (Table 4).

Another important point to note is the amplitude of the confidence intervals for the models (Table 3). The models generate by OLS method has a smaller amplitude of confidence intervals when compared to those generated by GLS method accommodating heteroscedasticity. This increase in amplitude is expected, since the model has precisely the objective of accommodating the existing variance between the observations.

The Logistic model is the most suitable for describing the growth of the cultivars Aguará 6 (Figures 3a-d) and Nusol 4510 (Figures 3e,f and 4a, b), as it presents a better fit on the data and lower values of AIC and BIC when compared to Gompertz (Table 4). For these cultivars, the Gompertz model underestimates the FPM values in the initial growing period, being therefore the most adequate logistic model.

The Gompertz model better describes the growth of the cultivar Rhino, although the AIC and BIC values are close those observed for Logistic model (Table 4), the curve given by Gompertz fits better on the data (Figures 4c-f). This cultivar has a different growth pattern from the others, since in the Gompertz model the inflection point is reached in 37% of the superior asymptote.

6.4.3 Fitting the models to the data

The Logistic and Gompertz models fit the data, converging on interpretable parameters (Table 2). The Logistic model is the most suitable for describing the growth of the cultivars Aguará 6 and Nusol 4510, while Gompertz model better describes the growth of the cultivar

Rhino. Therefore, the best model for each cultivar will be used to compare the growth between the trials.

It is possible to compare the parameters estimate of the best model within each cultivar, using as a criterion the overlapping of 95% confidence intervals ($CI_{95\%}$), used by Wheeler et al. (2006), Bem et al. (2017a) and Carini et al. (2020). According to these authors, when at least one of the parameter estimates is contained within the $CI_{95\%}$ of the other model, the difference is not significant.

Differences between the parameters for the three trials with the cultivar Aguará 6 (Table 2) are observed. The second trial presents the lowest value for parameter *a* (asymptote), being 1130.776 g. For the first and third trial the parameters are not different, based on the overlap of confidence intervals, and are respectively 1331.075 g and 1283.086 g. The highest value for parameter *b* (abscissa of the inflection point) is 846.8 °C observed in the first trial. In the second and third trial the value of *b* parameter is 715.634 °C and 737.999 °C respectively. The parameter *c* (growth rate) does not differ between trials.

Cultivar Nusol 4510, also better described by the Logistic model, presents a different behavior in relation to the growing season, only the parameter *c* is not different between the trials (Table 2). The highest values for *a* and *b* parameter are observed in the first trial, and are 1464.000 g and 865.000 °C, respectively. The second trial has the lowest values of asymptote (1069.255 g) and abscissa of the inflection point (719.399 °C), and was possibly penalized by some environmental factor. In the third test the values of *a* and *b* parameter are respectively 1296.000 g and 768.400 °C.

The Gompertz model best describes the growth of cultivar Rhino, *a* and *c* parameters estimated are not different between the trials (Table 2). Only *b* parameter differs for the three trials, showing increasing behavior from the first to the third trial. The observed inflection point abscissa (*b*) values for the first, second and third trials are, respectively, 616.706 °C, 676.800 °C and 768.500 °C.

6.5 DISCUSSION

6.5.1 Description of fresh plant mass accumulation and applications

Both models considered can be used to describe the fresh plant mass growth of sunflower cultivars. The study does not allow defining a single model as being the best, as the results show divergences between cultivars. The Logistic model is the most suitable for describing the growth of the cultivars Aguará 6 and Nusol 4510, while Gompertz model better describes the growth of the cultivar Rhino.

The Logistic model is the most used to describe growth curves, being defined as the most suitable for different cultures such as cocoa (Muniz et al., 2017), cashew (Muianga et al., 2016) and sugarcane (Jane et al., 2020b). However, the model has some limitations and because it is symmetrical in relation to the inflection point (Fernandes et al., 2014; Meade et al., 2013). This symmetry forced by the model, sometimes has no biological meaning, depending on the growth pattern and parameters *b* (abscissa of inflection point) and *c* (growth rate).

In the first trial with the cultivar Aguará 6 (Figure 3a), it is possible to see a situation in which this model presents a better fit, as the curve passes through all points without underestimating or overestimating the values, different from what is seen in the Figure 4d, where it is visible that the growth does not present a symmetrical pattern, but the model forces this behavior, overestimating the mass of plants in the initial period of growth. This behavior is also reported by Meade et al. (2013), when modeling the biomass accumulation of corn grains.

Still, in the first trials, the cultivars Aguará 6 and Nusol 4510 presented the highest value for parameter *b* compared to the other trials. Both cultivars have an early cycle, and are simple hybrids with high productive potential. When sown at the beginning of the recommended period, the plants have an advantage, as they have a longer period of positive and growing growth, and this behavior may be associated with hybrid vigor, since the environment did not present growth limitations. Similar results are demonstrated by Turchetto et al. (2021) in the cultivation of sunflower hybrids in three sowing dates, with the later times being penalized with reduced cycle, growth and yield.

The Gompertz model also presents relevant results, being easy to converge, when the appropriate initial parameters are used. In some situations, it performed better than the Logistic function, precisely because it is not symmetrical. The model presents the inflection point when it is reached in 37% of the upper asymptote (Jane et al., 2020b; Muianga et al., 2016). Despite the small variation in the criteria for assessing fit quality (Table 4), the Gompertz model best describes the growth of the Rhino cultivar in all situations, even considering heteroscedasticity in the first trial (Figures 4c-f).

The influence of the growth pattern is confirmed by differences in the abscissa of inflection point (*b*) presented in table 2 for the cultivar Rhino. The Gompertz model presents a lower parameter *b*, which shows the greater slope of the curve and the absence of a symmetrical growth pattern. Although the asymptote is not altered in the different growing seasons of the cultivar Rhino, it is observed that the cultivar presents a shorter time of positive growth in the first trial. It is characteristic of the cultivar to have greater precocity than the others used, and this behavior can be explained by the higher growth rate, when sown at the beginning of the recommended period.

When the sowings are carried out in a later period, the cultivar has its growth penalized, requiring more time to reach the inflection point. This behavior may be associated with a response of the cultivar to increasing photoperiod and the temperature-photoperiod interaction (Sentelhas et al., 1994). According to Wien (2014), some cultivars, when subjected to long days, may have a delayed or avoided flowering phase. Therefore, further studies must be carried out with the cultivar, taking into account the response to day length.

Other authors choose the Gompertz model as the most appropriate compared to the Logistic model for describing growth. Jane et al. (2020b) reports that the model is the most suitable for describing the growth of ratoon cane cycle. Fernandes et al. (2014) defines that the Gompertz model considering heteroscedasticity, is the most suitable to describe the growth of the coffee fruit.

When considering heteroscedasticity, when it occurs, the adjustment becomes more appropriate. This is visible with the Logistic Power and Gompertz Power models in the second experiment with the cultivar Aguará 6 (Figure 3b). This better adjustment is also confirmed by the adjustment criteria, as there is a significant reduction in AIC and BIC (Table 4). Similar results were observed by Xu et al. (2020), who, when considering the heteroscedasticity in the adjustment of the Logistic model to the biomass data of the *Caragana korshinskii* shrub, obtained a better fit.

6.6 CONCLUSIONS

The Logistic and Gompertz models adequately describe the fresh mass growth of sunflower plants. Both models converge in parameters with practical and biological interpretations. In the presence of heteroscedasticity, the insertion of the power structure to the models resulted in better adjustment of the models to the data. The cultivars Aguará 6 and Nusol 4510 are best described by the Logistic model and present higher positive growth phase in the first trial. The sunflower cultivar Rhino is best described by the Gompertz model and present reduction in positive growth phase in the first trial.

6.7 ACKNOWLEDGEMENTS

To the scholars and volunteers for their help in carrying out experiments and collecting data. To the Federal University of Santa Maria (UFSM), National Council for Scientific and Technological Development (CNPq), Research Support Foundation of the State of Rio Grande do Sul (FAPERGS) and to the Coordination for the Improvement of Higher Education Personnel (CAPES, Brazil - finance code 001) for scholarships. To the FAPERGS/CNPq by financial support (Process number 16/2551-0000257-6 ARD/PPP).

6.8 CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

6.9 REFERENCES

Akaike, H. (1974). A new look at the statistical model identification. IEEE Transactions on Automatic Control, 19, 716–723. https://doi.org/10.1109/tac.1974.1100705

Alvares, C. A., Stape, J. L., Sentelhas, P. C., de Moraes Gonçalves, J. L., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, 22, 711-728. https://doi.org/10.1127/0941-2948/2013/0507

Archontoulis, S. V., & Miguez, F. E. (2015). Nonlinear regression models and applications in agricultural research. Agronomy Journal, 107, 786-798. https://doi.org/10.2134/agronj2012.0506

Arnold, C. T. (1959). The determination and significance of the base temperature in a linear heat unit system. Proceedings of the American Society for Horticultural Science, 74, 430-455.

Bem, C. M. de, Cargnelutti Filho, A., Chaves, G. G., Kleinpaul, J. A., Pezzini, R. V., & Lavezo, A. (2017a). Gompertz and Logistic models to the productive traits of sunn hemp. Journal of Agricultural Science, 10, 225-238. https://doi.org/10.5539/jas.v10n1p225

Bem, C. M. de, Cargnelutti Filho, A., Facco, G., Schabarum, D. E., Silveira, D. L., Simões, F. M., & Uliana, D. B. (2017b). Growth models for morphological traits of sunn hemp. Semina: Ciências Agrárias, 38, 2933-2943. https://doi.org/10.5433/1679-0359.2017v38n5p2933

Carini, F., Cargnelutti Filho, A., Pezzini, R.V., Souza, J. M., Chaves, G. G ., & Procedi, A. (2020). Nonlinear models for describing lettuce growth in autumn-winter. Ciência Rural, 50, e20190534. https://doi.org/10.1590/0103-8478cr20190534

CQFS - Comissão de Química e Fertilidade do Solo (2016). Manual of fertilization and liming for the States of Rio Grande do Sul and Santa Catarina. Porto Alegre, Brazil: Sociedade Brasileira de Ciência do Solo. 376p

Fernandes, T. J., Pereira, A. A., Muniz, J. A., & Savian, T. V. (2014). Selection of nonlinear models for the description of the growth curves of coffee fruit. Coffee Science, 9, 207-215. https://doi.org/10.25186/cs.v9i2.618

Fonts, C., Andrade, F. H., Grondona, M., Hall, A., & León, A. J. (2008). Phenological characterization of near-isogenic sunflower families bearing two QTLs for photoperiodic response. Crop Science, 48, 1579-1585. https://doi.org/10.2135/cropsci2007.11.0604

Frühauf, A. C., de Assis Pereira, G., Barbosa, A. C. M. C., Fernandes, T. J., & Muniz, J. A. (2021). Nonlinear models in the study of the cedar diametric growth in a seasonally dry tropical forest. Revista Brasileira de Ciências Agrárias, 15, 4-11. https://doi.org /10.5039/agraria.v15i4a8558

Gilmore, E. C., & Rogers, J. S. (1958). Heat units as a method of measuring maturity in corn. Agronomy Journal, 50, 611-615. https://doi.org/10.2134/agronj1958.00021962005000100014x

Goyne, P. J., & Schneiter, A. A. (1987). Photoperiod influence on development in sunflower genotypes. Agronomy Journal, 79, 704-709. https://doi.org/10.2134/agronj1987.00021962007900040025x

Gratton, S., Lawless, A. S., & Nichols, N. K. (2007). Approximate Gauss–Newton Methods for Nonlinear Least Squares Problems. SIAM Journal on Optimization, 18, 106-132. https://doi.org/10.1137/050624935

Jane, S. A., Fernandes, F. A., Muniz, J. A., & Fernandes, T.J. (2020a). Nonlinear models to describe height and diameter of sugarcane RB92579 variety. Revista Ciência Agronômica, 51, e20196660. https://doi.org/10.5935/1806-6690.20200062

Jane, S. A., Fernandes, F. A., Silva, E. M., Muniz, J. A., Fernandes, T. J., & Pimentel, G.V. (2020b). Adjusting the growth curve of sugarcane varieties using nonlinear models. Ciência Rural, 50, e20190408. https://doi.org/10.1590/0103-8478cr20190408

Kaya, Y. (2020). Sunflower production in Blacksea Region: the situation and problems. International Journal of Innovative Approaches in Agricultural Research, 4, 147-155. https://doi.org/10.29329/ijiaar.2020.238.15

Mangueira, R. A. F., Savian, T. V., Muniz, J. A., Sermarini, R. A., & Crosariol netto, J. (2016). Logistic model considering different error distributions applied in maize height data. Revista Brasileira de Biometria, 34, 317-333. http://www.biometria.ufla.br/index.php/BBJ/article/view/143

Mazucheli, J., & Achcar, J. A. (2002). Considerations about nonlinear regression. Acta Scientiarum. Technology, 24, 1761-1770. https://doi.org/10.4025/actascitechnol.v24i0.2551

Mazzini, A. R. de A., Muniz, J. A., Aquino, L. H. de, & Silva, F. F. e. (2003). Análise da curva de crescimento de machos Hereford. Ciência e Agrotecnologia, 27, 1105-1112. https://doi.org/10.1590/s1413-70542003000500019

McMaster, G. S., & Smika, D. E. (1988). Estimation and evaluation of winter wheat phenology in the central Great Plains. Agricultural and Forest Meteorology, 43, 1-18. https://doi.org/10.1016/0168-1923(88)90002-0

Meade, K. A., Cooper, M., & Beavis, W. D. (2013). Modeling biomass accumulation in maize kernels. Field Crops Research, 151, 92-100. https://doi.org/10.1016/j.fcr.2013.07.014

Muianga, C. A., Muniz, J. A., Nascimento, M. D. S., Fernandes, T. J., & Savian, T. V. (2016). Description of the growth curve of cashew fruits in nonlinear models. Revista Brasileira de Fruticultura, 38, 22-32. https://doi.org/10.1590/0100-2945-295/14

Muniz, J. A., Nascimento, M. D. S., & Fernandes, T. J. (2017). Nonlinear models for description of cacao fruit growth with assumption violations. Revista Caatinga, 30, 250-257. https://doi.org/10.1590/1983-21252017v30n128rc

Pinheiro J., Bates D., DebRoy S., Sarkar D., & R Core Team. (2020). _nlme: Linear and Nonlinear Mixed Effects Models_. R package version 3.1-149. https://CRAN.R-project.org/package=nlme.

R Development Core Team (2020). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/

Regazzi, A. J., & Silva, C. H. O. (2010). Tests for model identity and parameter equality with nonlinear regression models in data from randomized complete block design. Revista Ceres, 57, 315-320. https://doi.org/10.1590/S0034-737X2010000300005

Ritz, C., & Streibig, J. C. (2008). Nonlinear regression with R. Springer, New York . 142p.

Schwarz, G. (1978). Estimating the Dimension of a Model. The Annals of Statistics, 6, 461-464. http://www.jstor.org/stable/2958889

Seber, G. A. F, & Lee A. J. (2003). Linear Regression Analysis. John Wiley, New York, 2ed. 557p.

Sentelhas, P. C. Nogueira, S. S. S., Pedro Júnior, & M. J. Santos, R. R. (1994). Base-temperature and degree-days to cultivars of sunflower. Revista Brasileira de Agrometeorologia, 2, 43-49. http://www.sbagro.org/files/biblioteca/37.pdf

Silva, N. S., Duarte, J. B., & Reis, A. J. S. (2015). Selection of the residual variance-covariance matrix in the analysis of varietal trials with repeated measures in sugarcane. Ciência Rural, 45, 993-999. https://doi.org/10.1590/0103-8478cr20141531

Silva, W. F., Fernandes, F. A., Muniz, F. R., Muniz, J. A, & Fernandes, T. J. (2021). *Eucalyptus Grandis* x *Eucalyptus Urophylla* growth curve in different site classifications, considering residual autocorrelation. Revista Brasileira de Biometria, 39, 122-138. https://doi.org/10.28951/rbb.v39i1.511

Sousa, I. F., Neto, J. E. K., Muniz, J.A., Guimarães, R. M., Savian, T. V., & Muniz, F. R. (2014). Fitting nonlinear autoregressive models to describe coffee seed germination. Ciência Rural, 44, 2016–2021. https://doi.org/10.1590/0103-8478cr20131341

Streck, N. A., Bosco, L. C., Lucas, D. D. P., & Lago, I. (2008). Modeling leaf appearance in cultivated rice and red rice. Pesquisa Agropecuária Brasileira, 43, 559-567. https://doi.org/10.1590/S0100-204X2008000500002

Turchetto, R., Trombetta, L. J., Rosa, G. M. da, Volpi, G. B., Barros, S. (2021). Production components of sunflower cultivars at different sowing times. Pesquisa Agropecuária Tropical, 51, e68137. https://doi.org/10.1590/1983-40632021v5168137

USDAa. Foreign Agricultural Service. (2021). Oilseeds: world market and trade. March 2021. 39p

USDAb. Foreign Agricultural Service. (2021). World Agricultural Production. March 2021. 40p

Villalobos, F. J., Hall, A. J., Ritchie, J. T., & Orgaz, F. (1996). Oilcrop-Sun: A development, growth, and yield model of the sunflower crop. Agronomy Journal, 88, 403-415. https://doi.org/10.2134/agronj1996.00021962008800030008x

Wheeler, M. W., Park, R. M., & Bailer, A. J. (2006). Comparing median lethal concentration values using confidence interval overlap or ratio tests. Environmental Toxicology and Chemistry, 25, https://doi.org/1441-1444. 10.1897/05-320R.1

Wien, H.C. (2014). Screening Ornamental Sunflowers in the Seedling Stage for Flowering Reaction to Photoperiod. HortTechnology, 24, 575-579. https://doi.org/10.21273/HORTTECH.24.5.575

Wickham, H. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York, 2016.

Xu, H., Wang, Z., Li, Y., He, J., & Wu, X. (2020). Dynamic growth models for Caragana korshinskii shrub biomass in China. Journal of Environmental Management, 269, 110675. https://doi.org/10.1016/j.jenvman.2020.110675

Zeileis, A., & Hothorn, T. (2002) Diagnostic Checking in Regression Relationships. R News 2, 7-10. https://CRAN.R-project.org/doc/Rnews/

6.10 TABLES

Table 1

P-value of the Shapiro-Wilk, Durbin-Watson and Breusch-Pagan tests, applied to the residues of the Logistic and Gompertz models, adjusted to the fresh plant mass of sunflower cultivars.

Cultivar	Trial	Model	Shapiro-Wilk	Durbin -Watson	Breusch - Pagan
Aguará 6	First	Logistic	0.081	0.022	0.002 *
		Gompertz	0.021	0.022	0.020
	Second	Logistic	0.040	0.112	0.001 *
		Gompertz	0.035	0.236	0.002 *
	Third	Logistic	0.742	0.058	0.003 *
		Gompertz	0.814	0.030	0.020
	All	Logistic	0.149	0.108	0.111
		Gompertz	0.173	0.226	0.287
Nusol 4510	First	Logistic	0.681	0.214	0.079
		Gompertz	0.285	0.046	0.059
	Second	Logistic	0.251	0.096	0.001 *
		Gompertz	0.376	0.080	0.003 *
	Third	Logistic	0.014	0.846	0.076
		Gompertz	0.027	0.184	0.099
	All	Logistic	0.141	0.644	0.013
		Gompertz	0.360	0.124	0.014
Rhino	First	Logistic	0.025	0.788	0.002 *
		Gompertz	0.020	0.948	0.003 *
	Second	Logistic	0.012	0.114	0.033
		Gompertz	0.143	0.150	0.023
	Third	Logistic	0.171	0.522	0.202
		Gompertz	0.262	0.478	0.059
	All	Logistic	0.100	0.288	0.020
		Gompertz	0.080	0.322	0.041

* significant, i.e., p-value <0.01.

Table 2

Estimates for the parameters of the Logistic and Gompertz models adjusted to the accumulation of fresh plant mass in sunflower cultivars, and their respective lower limit (LL) and upper limit (UL) of the asymptotic confidence intervals ($CI_{95\%}$).

		Logistic			Gompertz		
Cultivar	Trial	LL	Mean	UL	LL	Mean	UL
Aguará 6	First						
	a	1154.567	1331.075$^{\text{A (1) *}}$	1507.583	1273.451	1400.000	1566.562
	b	803.390	846.800$^{\text{A}}$	890.209	733.726	770.800	810.367
	c	0.007	0.008$^{\text{A}}$	0.008	0.004	0.005	0.006
	Second						
	a	1010.470	1130.776$^{\text{B*}}$	1251.082	1046.443	1246.842*	1447.242
	b	682.404	715.634$^{\text{B}}$	748.864	620.360	666.392	712.424
	c	0.008	0.009$^{\text{A}}$	0.010	0.004	0.005	0.006
	Third						
	a	1171.296	1283.086$^{\text{A*}}$	1394.876	1198.065	1278.000	1374.797
	b	699.343	737.999$^{\text{B}}$	776.655	625.795	665.600	699.067
	c	0.007	0.008$^{\text{A}}$	0.009	0.004	0.006	0.009
	All						
	a	1194.465	1242.000	1295.144	1258.226	1322.000	1400.973
	b	748.821	770.500	792.179	674.015	694.700	717.711
	c	0.006	0.007	0.008	0.004	0.004	0.005
		LL	Mean	UL	LL	Mean	UL
Nusol 4510	First						
	a	1395.199	1464.000$^{\text{A}}$	1539.475	1446.051	1551.000	1690.458
	b	839.177	865.000$^{\text{A}}$	892.300	758.766	788.100	820.075
	c	0.006	0.008$^{\text{A}}$	0.009	0.004	0.004	0.006
	Second						
	a	965.059	1069.255$^{\text{C*}}$	1173.451	1005.834	1221.123*	1436.412
	b	685.240	719.399$^{\text{C}}$	753.559	620.810	674.557	728.304
	c	0.008	0.009$^{\text{A}}$	0.010	0.003	0.004	0.005
	Third						
	a	1213.923	1296.000$^{\text{B}}$	1390.069	1259.498	1386.000	1559.942
	b	733.437	768.400$^{\text{B}}$	804.658	639.342	684.000	730.745
	c	0.006	0.007$^{\text{A}}$	0.009	0.003	0.004	0.005
	All						
	a	1227.362	1282.000	1342.088	1283.137	1371.000	1484.893
	b	760.152	783.600	808.609	678.475	706.300	737.207
	c	0.006	0.007	0.009	0.004	0.004	0.005
		LL	Mean	UL	LL	Mean	UL
Rhino	First						
	a	1046.218	1187.627*	1329.037	1094.831	1319.214$^{\text{A*}}$	1543.598
	b	630.883	673.094	715.305	567.048	616.706$^{\text{C}}$	666.363
	c	0.008	0.009	0.010	0.004	0.005$^{\text{A}}$	0.005
	Second						
	a	1044.004	1126.000	1235.623	1116.529	1244.000$^{\text{A}}$	1446.617
	b	708.012	748.900	799.321	634.132	676.800$^{\text{B}}$	738.087
	c	0.005	0.007	0.008	0.003	0.004$^{\text{A}}$	0.005
	Third						
	a	1015.928	1102.000	1212.028	1098.336	1248.000$^{\text{A}}$	1489.964
	b	797.245	839.200	6.191	717.235	768.500$^{\text{A}}$	845.358
	c	0.005	0.006	0.008	0.003	0.003$^{\text{A}}$	0.004
	All						
	a	1044.062	1104.000	1173.916	1101.788	1191.000	1312.290
	b	708.340	737.800	770.215	632.188	662.800	699.292
	c	0.006	0.007	0.009	0.003	0.004	0.005

*Power Models - Considering heteroscedasticity. (1)Comparison of parameter estimates (*a*, *b* and *c*) between trials for the Logistic (Cultivars - Aguará 6 and Nusol 4510), and for the Gompertz model (Cultivar - Rhino). Averages followed by the same capital letter in column do not differ between trials.

Table 3

Estimates for the parameters of the Logistic and Gompertz models adjusted to the accumulation of fresh mass in sunflower plants, disregarding violation of homoscedasticity and their respective lower limit (LL) and upper limit (UL) of the asymptotic confidence intervals ($CI_{95\%}$).

		Logistic			Gompertz		
Cultivar	Trial	LL	Mean	UL	LL	Mean	UL
Aguará 6	First						
	a	1233.666	1327.000	1430.736	-	-	-
	b	811.497	845.700	881.841	-	-	-
	c	0.006	0.008	0.010	-	-	-
	Second						
	a	1055.194	1159.000	1333.394	1121.963	1281.000	1601.772
	b	678.395	726.700	807.355	624.235	673.200	762.261
	c	0.005	0.008	0.012	0.003	0.004	0.006
	Third						
	a	1188.981	1258.000	1330.445	-	-	-
	b	697.061	730.600	765.189	-	-	-
	c	0.007	0.009	0.012	-	-	-
		LL	Mean	UL	LL	Mean	UL
Nusol 4510	Second						
	a	1005.714	1069.000	1145.014	1046.812	1140.000	1278.620
	b	688.065	719.400	755.805	620.997	655.100	695.903
	c	0.007	0.009	0.011	0.004	0.005	0.007
		LL	Mean	UL	LL	Mean	UL
Rhino	First						
	a	1091.185	1197.000	1330.993	1120.691	1264.115	1502.452
	b	627.834	675.800	731.075	557.597	606.987	666.152
	c	0.006	0.008	0.012	0.003	0.005	0.008

Table 4

Criteria for assessing the quality of fit for the Logistic and Gompertz models adjusted to the accumulation of fresh plant mass in sunflower cultivars.

			Considering homoscedasticity (OLS)			Considering heteroscedasticity (GLS)		
Cultivar	Trial	Model	(R^2_{adj})	AIC	BIC	(R^2_{adj})	AIC	BIC
Aguará 6	First	Logistic	0.954	557.759	564.985	0.954	495.904	504.938
		Gompertz	0.949	562.663	569.890	-	-	-
	Second	Logistic	0.926	574.495	581.721	0.925	498.598	507.632
		Gompertz	0.932	570.181	577.408	0.932	492.169	501.203
	Third	Logistic	0.937	572.157	579.384	0.935	561.043	570.076
		Gompertz	0.932	576.922	584.149	-	-	-
	All	Logistic	0.984	504.439	511.666	-	-	-
		Gompertz	0.986	498.333	505.559	-	-	-
Nusol 4510	First	Logistic	0.972	543.839	551.066	-	-	-
		Gompertz	0.856	599.925	607.151	-	-	-
	Second	Logistic	0.956	542.595	549.821	0.956	498.755	507.788
		Gompertz	0.954	544.750	551.976	0.952	488.799	497.832
	Third	Logistic	0.958	552.618	559.844	-	-	-
		Gompertz	0.948	562.164	569.391	-	-	-
	All	Logistic	0.980	517.590	524.817	-	-	-
		Gompertz	0.976	527.038	534.264	-	-	-
Rhino	First	Logistic	0.910	586.103	593.330	0.910	530.657	539.691
		Gompertz	0.909	586.710	593.937	0.908	508.223	517.256
	Second	Logistic	0.959	536.268	543.494	-	-	-
		Gompertz	0.962	532.196	539.423	-	-	-
	Third	Logistic	0.960	528.245	535.471	-	-	-
		Gompertz	0.958	529.168	536.395	-	-	-
	All	Logistic	0.973	517.050	524.277	-	-	-
		Gompertz	0.973	516.401	523.628	-	-	-

6.11 FIGURES

FIGURE LEGENDS

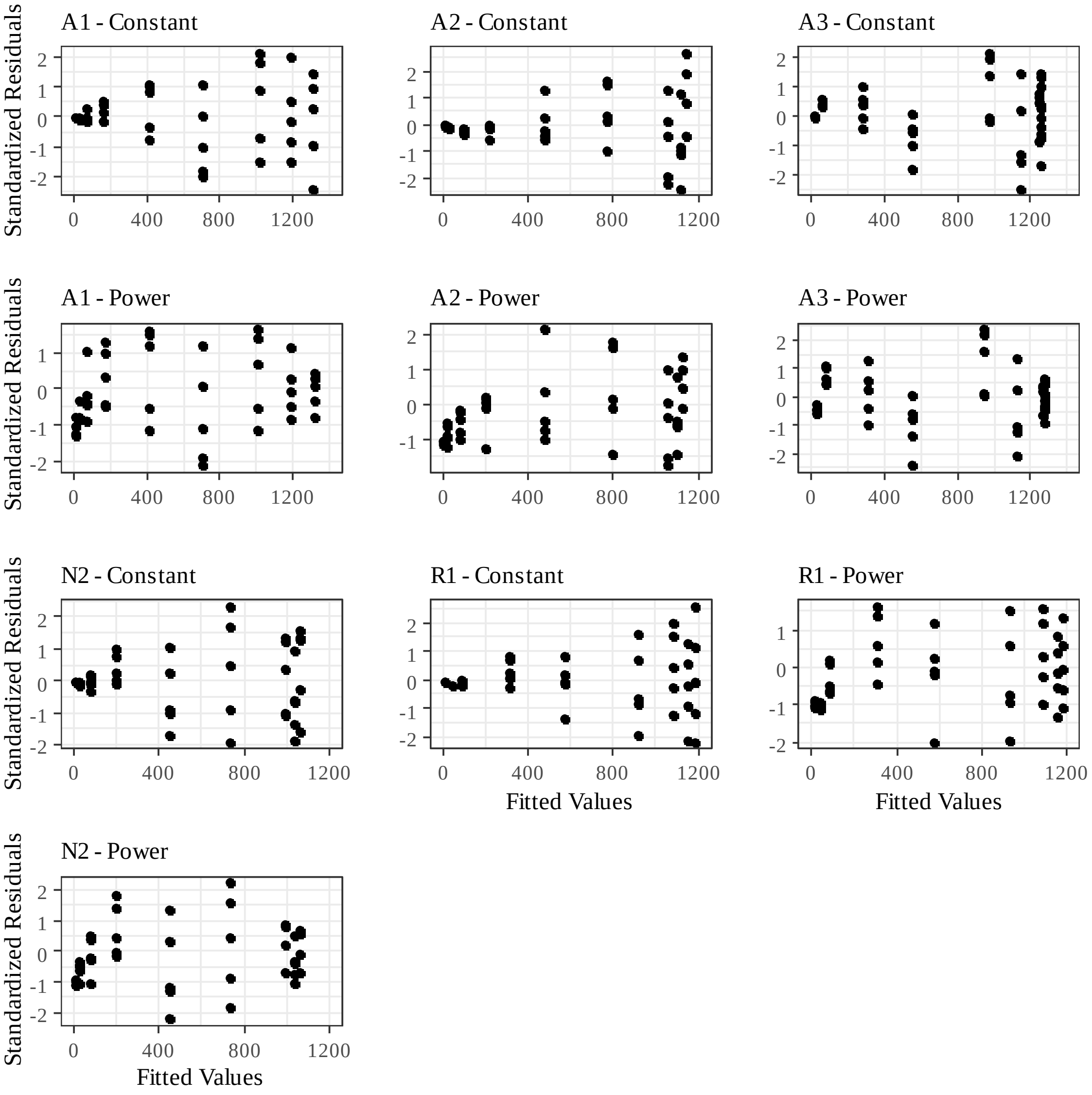
FIGURE 1 – Standardized residuals for the Logistic model considering homoscedasticity (Constant model), and which assumes the heteroscedasticity (Power model), adjusted to the fresh plant mass of sunflower plants. A1- First trial, A2 - Second trial and A3 - Third trial with Aguará 6. N2 - Second trial with Nusol 4510. R1 - First trial with Rhino.

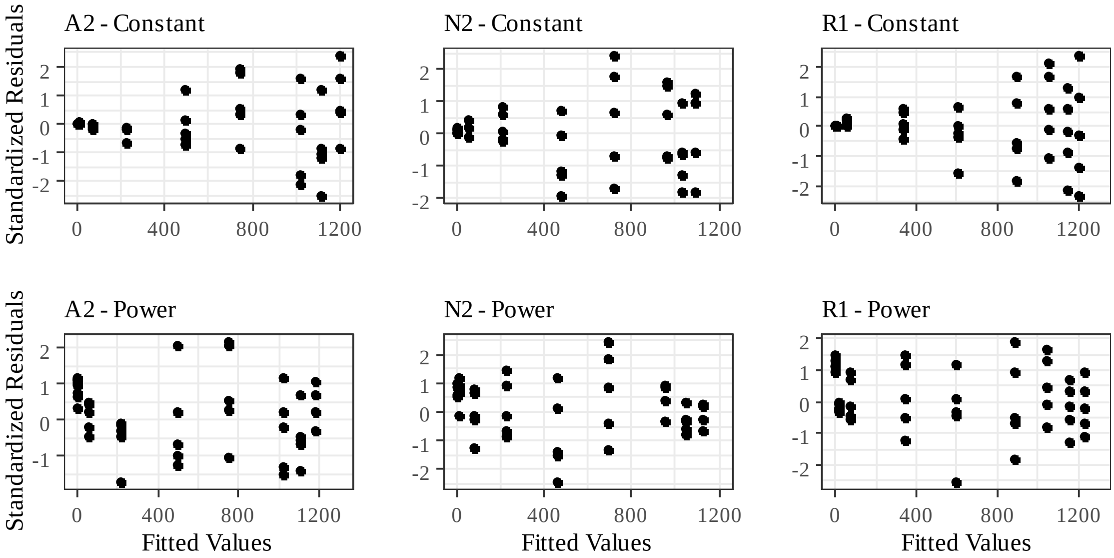
FIGURE 2 – Standardized residuals for the Gompertz model considering homoscedasticity (Constant model), and which assumes the heteroscedasticity (Power model), adjusted to the fresh plant mass of sunflower plants. A2 - Second trial with Aguará 6. N2 - Second trial with Nusol 4510. R1 - First trial with Rhino.

FIGURE 3 – Adjustment of the Logistic and Gompertz models to the fresh plant mass data of sunflower cultivars as a function of the accumulated growing degree days (GDD). a) First trial, b) Second trial, c) Third trial and, d) Fourth situation (All) with Aguará 6. e) First trial and, f) Second trial with Nusol 4510.

FIGURE 4 – Adjustment of the Logistic and Gompertz models to the fresh plant mass data of sunflower cultivars as a function of the accumulated growing degree days (GDD). a) Third trial and, b) Fourth situation (All) with Nusol 4510. c) First trial, d) Second trial, e) Third trial and, f) Fourth situation (All) with Rhino.

FIGURES


A1 - Constant
A2 - Constant
A3 - Constant
A1 - Power
A2 - Power
A3 - Power
N2 - Constant
R1 - Constant
R1 - Power
N2 - Power
Standardized Residuals
Fitted Values
2
1
0
-1
-2
0
400
800
1200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N2 - Constant
R1 - Constant
A2 - Power
N2 - Power
R1 - Power
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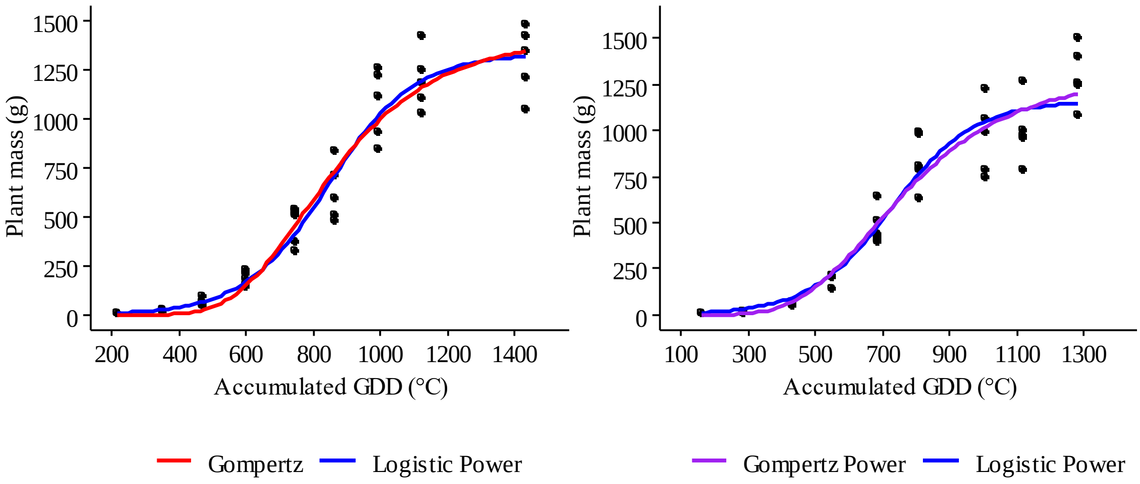
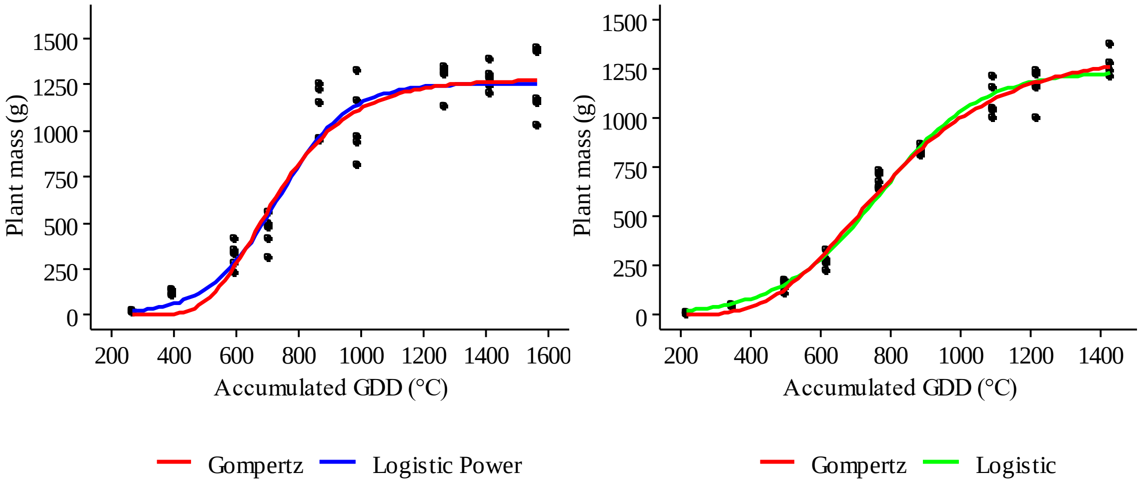
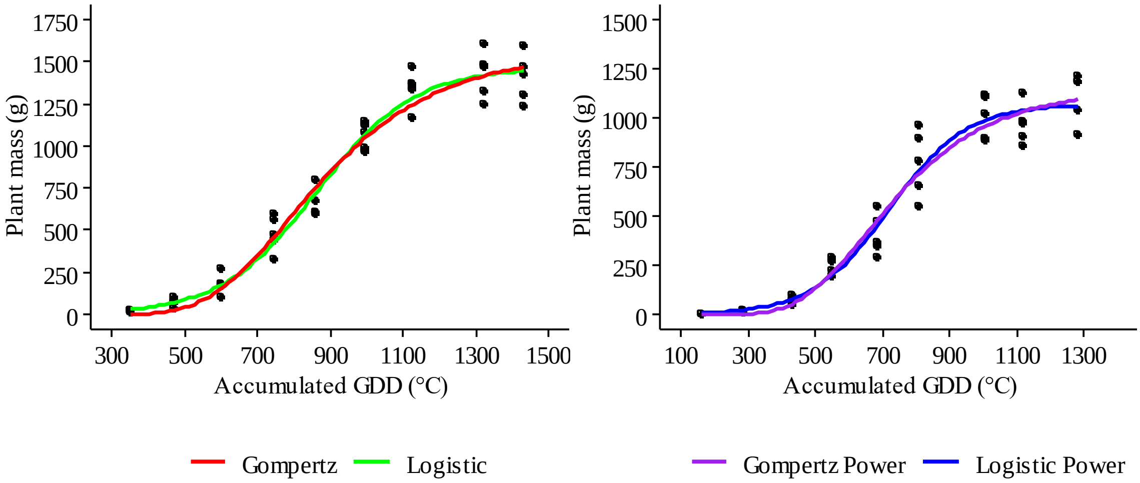

a) First trial- Aguará 6

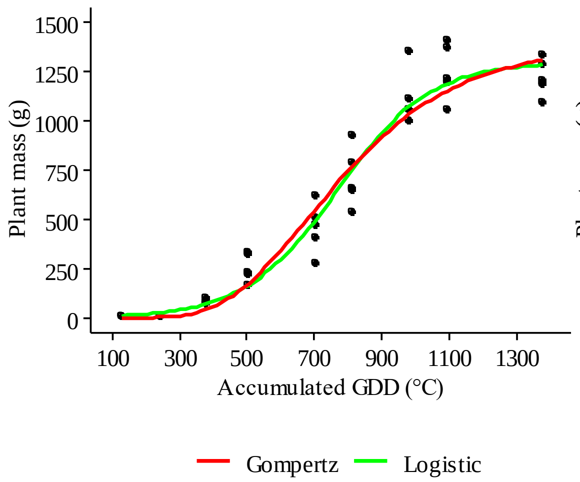
b) Second trial - Aguará 6

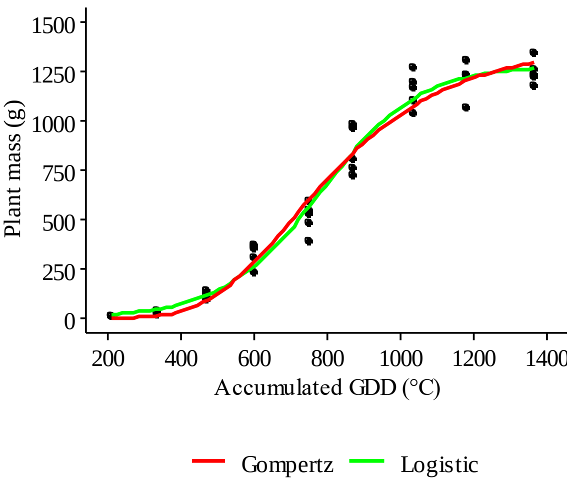

c) Third trial - Aguará 6

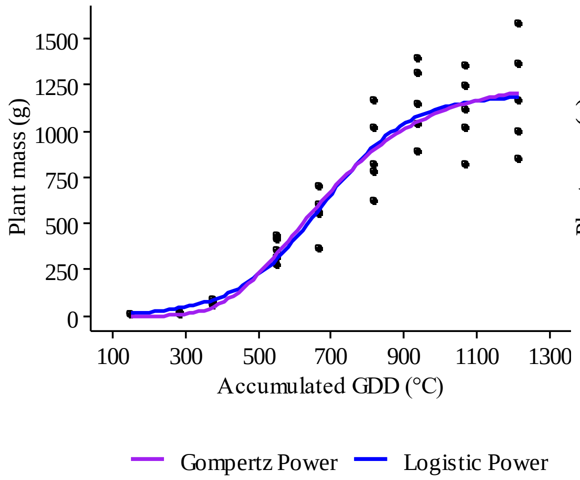
d) Aguará 6

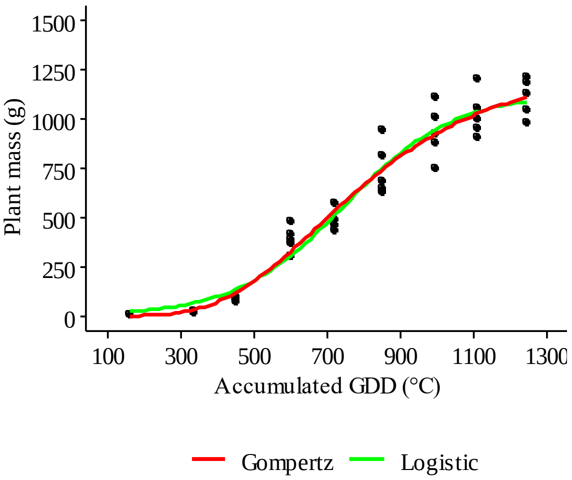

e) First trial - Nusol 4510

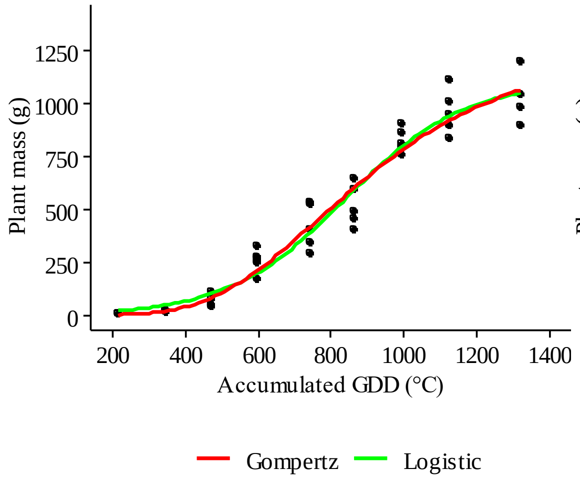
f) Second trial - Nusol 4510

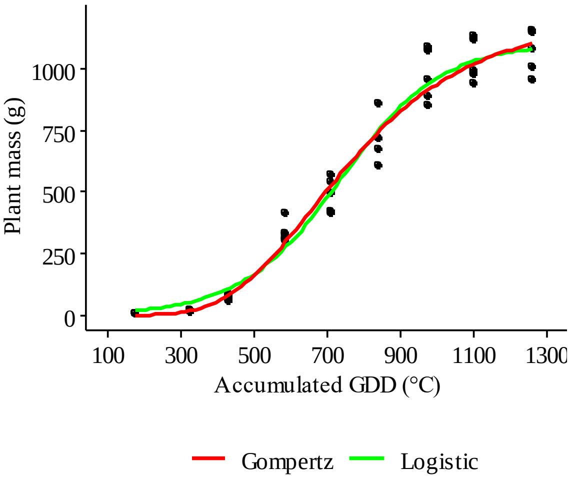

a) Third trial - Nusol 4510


b) Nusol 4510


c) First trial - Rhino


d) Second trial - Rhino


e) Third trial - Rhino


f) Rhino

7. ARTIGO III – NONLINEAR MODELS TO DESCRIBE THE DEVELOPMENT USING NUMBER OF LEAVES OF SUNFLOWER CULTIVARS

(Formatação da revista Scientia Agricola)

Submetido para o periódico: Scientia Agricola

Situação: Sob revisão

Nonlinear models to describe the development using number of leaves of sunflower cultivars

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° Part of the Master’s dissertation to be presented in the Agronomy Postgraduate Program - Agriculture and Environment by the first author.

7.1 ABSTRACT

Sunflower (*Helianthus annuus* L.) originates from America and produces very high-quality oil. Modeling is an indispensable tool for characterizing growth and development, as it allows simulating the real response of plants. This study aimed to use the Logistic, Brody, Gompertz and von Bertalanffy models to describe the growth curve in number of leaves of three sunflower cultivars sown in three times, and define the coordinates of the critical growth points of the best models. The data used come from nine uniformity trials with three sunflower cultivars, conducted in the Federal University of Santa Maria - Campus Frederico Westphalen-RS-Brazil in the 2019/2020 harvest. The leaf number data were adjusted as a function of the accumulated growing degree days using the method of ordinary squares. The Logistic model is more suitable for Aguará 6 and Rhino cultivars while Gompertz is more suitable for Nusol 4510. Brody should not be used in the description the leaf number of sunflower cultivars. Critical points allow to differentiate as cultivars according to the growth pattern, Aguará 6 and Rhino reach the inflection point (IP) at 50% of the asymptote, while Nusol 4510 reaches the IP at 37% of the asymptote.

Keywords: Growth curve, *Helianthus annuus* L., Nonlinear regression, Critical points.

7.2 INTRODUCTION

Sunflower (*Helianthus annuus* L.) is native from the American continent and was domesticated by natives of the eastern United States, widely cultivated as an oilseed in tropical and subtropical climate regions of about 72 countries (Seiler and Gulya, 2016). The crop has gained space among oil producers, currently occupying the third position, only behind soybeans [*Glycine max* (L.) Merr.] and rapeseed (*Brassica napus* L.) (USDA, 2021). Oil production is the main purpose, as in addition to its high content (39 to 50%), sunflower oil has a superior quality to other oils, due to a higher proportion of unsaturated fatty acids such as oleic, linoleic and linolenic, in addition to not having trans fats (Seiler and Gulya, 2016; Castro and Leite, 2018; Kaya, 2020).

Modern cultivars are very different from their primitive ancestors. The gains in productivity, adaptability and resistance, among others, are due to the advances achieved with numerous researches in different countries. There are specific cultivars for each desired purpose, with visible morphological differences in the plants in response to genetic potential, management and cultivation environment. This fact leverages the need to know the growth pattern of plants, which allows making simulations and inferences about the growth.

Several authors use growth and development modeling in studies with agricultural crops. Jane et al. (2019) compared the fit of Polynomial, Logistic and Gompertz models to describe the growth of pepper plants. Jane et al. (2020a) evaluated the fit of the Logistic, Brody, Gompertz and von Bertalanffy models in the description of height and diameter of sugarcane. Likewise, Frühauf et al. (2021) used the Logistic, Brody, Gompertz, and von Bertalanffy models to characterize the diameter growth of cedar (*Cedrela fissilis* Vell.). Other authors have also used models to describe the growth and development of crops such as cocoa (Muniz et al., 2017), sunn hemp (Bem et al., 2017b), coffee (Fernandes et al., 2014), green dwarf coconut (Silva et al., 2021), among others.

Many models for studying growth and development curves of plants, fruits and other living beings are available in the literature. However, non-linear models are preferable to linear models, as according to Mischan and Pinho (2014), the growth of living beings presents a distinct response, starting slowly, moving to an exponential phase and tending to stabilize at the end. Associated with this, nonlinear models are more parsimonious and have parameters with practical and biological interpretation, being recommended by several authors to describe growth and development (Pereira et al. 2014; Sousa et al., 2014; Archontoulis and Miguez, 2015).

According to Mazzini et al. (2003), the most used nonlinear functions in the description of growth curves are those of Richards, Gompertz, von Bertalanffy, Brody and Logistic. In the present study, the Logistic, Brody, Gompertz, and von Bertalanffy models will be used, considering their most usual parameterization available in the literature.

All models to be used have three parameters. Logistic, Gompertz, and von Bertalanffy are sigmoid, while Brody does not exhibit this response (Brody, 1945). Among these models, the Logistic is the most used and has the characteristic of being symmetrical in relation to the inflection point, that is, 50% of the upper asymptote is reached at the inflection point, while in the Gompertz model the inflection point is reached in 37% of the superior asymptote (Fernandes et al., 2014). According to some authors, the Logistic model has some limitations due to this symmetry, which is sometimes forced, losing part of the biological sense, depending on the growth pattern and the adjusted b (scale parameter) and c (growth rate) parameters (Meade et al., 2013).

Brody and von Bertalanffy models are normally associated with animal growth curves, but some parameterizations are applied to plant growth with positive results. For the von

Bertalanffy model, the inflection point is reached at approximately 30% of the asymptote (Mischan and Pinho, 2014). The Brody model has an inflection parameter (*m*) equal to zero, that is, there is no definition of the inflection point as in the other models, the curve has two curve segments called "growth acceleration phase" and "growth self-inhibition phase", which are delimited when about one-third of the asymptote is reached (Tholon and Queiroz, 2007).

According to Silva et al. (2021) growth curves do not present extreme, maximum or minimum points, but some critical points are important, having a specific meaning. Mischan and Pinho (2014), defined these points for the equations of the Logistic, Gompertz and von Bertalanffy models, through the derivatives of the equations in relation to time.

In this sence, many authors have used critical points of nonlinear models in the field of agricultural sciences, as they provide relevant information on the growth and development of plants and fruits (Kleinpaul et al., 2019; Carini et al., 2020; Silva et al., 2020; Silva et al., 2021; Mello et al., 2022).

There are numerous conflicting results regarding the response of sunflower to photoperiod (Goyne and Schneiter, 1987; Villalobos et al., 1996; Fonts et al., 2008), but it is known that temperature is a limiting factor for plant growth, mainly in critical phases (De La Haba et al., 2020). Thus, since mathematical models must be able to reproduce the response of plants as realistically as possible (Carini et al., 2020), several authors choose to model plant growth in relation to the growing degree days , since this is a more accurate biological measure of time than the civil calendar (Gilmore and Rogers, 1958; McMaster and Smika, 1988).

Given the above, this study aims to use the nonlinear models, Logistic, Brody, Gompertz and von Bertalanffy to model the development curve using the number of leaves of three sunflower cultivars sown in three times, and define the coordinates of the critical points of the models that present the best fit.

7.3 MATERIAL AND METHODS

7.3.1 Characterization of the experimental design

Nine uniformity tests (blank experiments) were carried out with sunflower crop at the Federal University of Santa Maria in Frederico Westphalen – RS – Brazil, during the 2019/2020 harvest. According to Köppen the soil in the area is classified as Red Oxisol. Alvares et al. (2013) classify the climate as Cfa. The study was carried out with three sunflower cultivars, destined for two purposes, in three sowing dates, within the recommended period for the crop. Cultivar Rhino destined for the production of confectionery grains was sown on September 23, 2019 (R1), October 7, 2019 (R2) and October 23, 2019 (R3). Cultivar Nusol 4510 on October 23, 2019 (N1), November 6, 2019 (N2) and November 22, 2019 (N3) and Aguará 6 on October 23, 2019 (A1), November 6, 2019 (A2) and November 29, 2019 (A3). Nusol 4510 and Aguará 6 are intended for oil extraction. Sowing was performed manually with 0.5 m spacing between rows and 0.33 m between plants. Two seeds were placed per point with subsequent thinning to obtain the recommended population of 60,000 plants ha^{-1}. Each of the trials consisted of a 250 m^2 strip, containing 10 lines (5 m) by 50 m in length. Fertilization was carried out according to soil analysis and crop recommendations (CQFS, 2016), with 10 kg ha^{-1} of N, 70 kg ha^{-1} of K_2O and 60 kg ha^{-1} of P_2O_5 being applied at sowing and 50 kg ha^{-1} of N 30 days after emergence. All cultural practices were carried out uniformly in the experimental area.

7.3.2 Calculation of accumulated growing degree days

The data of the number of leaves per plant were adjusted as a function of the accumulated growing degree days (GDD) after the emergency, calculated according to the method of

Gilmore and Rogers (1958) and Arnold (1959), with a base temperature of 4.2 °C according to determinations made by Sentelhas et al. (1994). The meteorological data used come from the automated station, located about 500 m from the experimental area with the following geographic coordinates, latitude 27º23’44" S and longitude 53º25’46" W and linked to the National Institute of Meteorology (INMET).

7.3.3 Description of the number of leaves by nonlinear models

The models Logistic (1), Brody (2), Gompertz (3) and von Bertalanffy (4) were used according to the equations:

(1) $yi = \frac{a}{1+e^{(b-c*x_i)}} + \varepsilon_i$

(2) $yi = a(1 - b\,e^{(-c*x_i)}) + \varepsilon_i$

(3) $yi = ae^{[-e^{(b-c*x_i)}]} + \varepsilon_i$

(4) $yi = a(1 - b\,e^{(-c*x_i)})^3 + \varepsilon_i$

where, yi represents the observed values of the number of leaves for $i = 1, 2, ..., n$ observations as a function of the independent variable (GDD), and x_i is the i^{th} measurement time of the independent variable, a represents the asymptotic value of the dependent variable, b is an important parameter to maintain the shape of the curve, and c is related to the growth rate, the higher the value of parameter c, the shorter the time needed to reach the asymptote (a), and ε_i corresponds to the random error, assumed to be independently and identically distributed following a normal distribution with a mean of zero and constant variance, that is, $\varepsilon_i \sim N(0,\sigma^2)$.

Weekly evaluations of the number of leaves (NL) were carried out in 10 plants per trial collected randomly. The evaluations started as soon as the first true leaves expanded, being considered expanded leaves those greater than 4 cm in length from the base of the blade to the extremity, as proposed by Schneiter and Miller (1981).

Were evaluated 1030 plants from the nine trials. For the generation of the models, nine evaluations were used, since the growth in the number of leaves had already reached the asymptote and stabilized. The objective was to standardize the fit raters as they are dependent on the number of parameters and evaluations (Akaike, 1974; Schwarz, 1978; Seber and Lee, 2003). The models were generated by the average of the ten observations. For each cultivar, 16 models were generated, considering four models and four situations: first trial, second trial, third trial and the average of the three trials (All).

7.3.4 Parameters estimation and residuals analysis

The estimation of parameters was performed using the Gauss-Newton method, which is also known as the linearization method (Regazzi and Silva, 2010), this linearization is done through the expansion of the first-order Taylor series (Wang, 2012). It is necessary to use this iterative method because, in the study of non-linear equations, the system of normal equations does not have a closed-form (Fernandes et. al., 2014). With this, from an initial value for the parameters, entered by the researcher, the software performs the iterative process of Gauss-Newton until the convergence of the parameter to the real value (Mazucheli and Achcar, 2002).

The significance of parameters was verified by the t-test at a level of 1%, testing the null hypothesis that the parameters are equal to zero ($\theta i = 0$), that is, they do not contribute to the model, against the alternative hypothesis ($\theta i \neq 0$), that is, parameters are different from zero and contribute to the model (Jane et al., 2020a). Residual assumptions were verified using Shapiro-Wilk, Breusch-Pagan and Durbin-Watson tests, for normality, homogeneity and independence, respectively (Ritz and Streibig, 2008). The $p\text{-value}<0.01$ was adopted as significant, so models that violate the assumptions are not considered adequate for the description of growth, and corrective measures should be adopted. Disregarding assumption violations can result in biased and inaccurate estimates with values below or above the true (Sousa et al., 2014).

7.3.5 Diagnostic and comparison methods

For the diagnosis of fit goodness, five evaluators were used, such as the adjusted coefficient of determination (R^2_{adj}), Akaike's information criterion (AIC), Schwarz's Bayesian criterion (BIC), and through intrinsic nonlinearity (IN) and parametric (PE) using the Bates and Watts curvature method (Bates and Watts, 1988). Higher values of R^2_{adj} and lower values of AIC and BIC are associated with better fit models (Akaike, 1974; Schwarz, 1978; Seber and Lee, 2003).

The evaluators R^2_{adj} (5), AIC (6) and BIC (7) are given by the equations:

(5) $R^2_{adj} = 1 - \left[\frac{(n-1)}{n-(p-1)}\right](1 - R^2)$

(6) $AIC = -2\log L(\hat{\theta}) + 2(p)$

(7) $BIC = -2\log L(\hat{\theta}) + p.\log(n)$,

where: p is the number of parameters, R^2 is the coefficient of determination, n is the number of observations in the sample and $log\ L(\hat{\theta})$ is the logarithm value of the of the likelihood function evaluated in the parameter estimates.

As the models are obtained through linearization processes, the estimates must have characteristics close to the estimates of a linear model. Therefore, it is important to use non-linearity measures, which make it possible to make inferences about how close a non-linear model is to the linear model. Therefore, as proposed by Bates and Watts (1988), the IN and PE nonlinearity coefficients were calculated. When the model's response is not close to linear, parameter estimates are biased, confidence intervals are not accurate and hypotheses cannot be tested (Bates and Watts, 1988; Seber and Wild, 2003; Ritz and Streibig, 2008)

Yet, to compare the models, confidence intervals were built using the *confint.default* function of the stats package of the R software (R Core Team, 2020). The 95% confidence intervals ($IC_{95\%}$) for the parameters were used to compare the parameters between the trials, cultivars and models, based on the overlapping confidence interval (IC) criterion according to the methodology used by Wheeler et al. (2006), by Bem et al. (2017a) and by Carini et al. (2020). According to these authors, when at least one of the parameter estimates is contained within the CI of the other, the difference is not significant.

7.3.6 Software

All statistical analyzes were performed using the R software (R Core Team, 2020). The nonlinear models were adjusted using the *nls* function, available in the *stats* (R Core Team, 2020) packages. Residue analyzes were performed using the functions *shapiro.test* (R Core Team, 2020), *bptest* and *dwtest* (*lmtest* package, Zeileis and Hothorn, 2002), used for normality, heteroscedasticity and independence, respectively. Confidence intervals were generated using the *confint* function of the *stats* package (R Core Team, 2020). The graphics were built using *ggplot2* (Wickham, 2016) packages.

7.4 RESULTS

7.4.1 Models fit and assumptions

Table 1 shows that assumptions violations of normality, independence and homoscedasticity were not observed for all studied situations ($p>0.01$), based on the Shapiro-Wilk, Durbin-Watson and Breusch-Pagan tests.The estimated parameters for the cultivar

Aguará 6 and their respective confidence intervals are shown in table 2. The estimates were significant for the t-test ($p < 0.01$), except for the Brody model, in A1 and A3, where obtained parameters *c* non-significant, that is, in these situations, the hypothesis that the parameters are equal to zero and do not contribute to the adjusted model is accepted.

It should also be noted that smaller amplitudes of confidence intervals were obtained for the Logistic, Gompertz and von Bertalanffy models (Table 2). Brody's model, in A1 and A3 presented high confidence intervals for parameter *a* and non-zero interval for parameter *c*, indicating that this model is not suitable to describe the development of these trials.

Comparing the estimated parameters for the different models, based on the overlapping confidence intervals criterion, it was observed that in the three trials there is no difference between the estimates for parameter *a* (Table 2). The Logistic, Gompertz, Brody and von Bertalanffy models estimated respectively 30.887, 31.736, 37.593 and 32.250 leaves as asymptotes for A2. The Brody model did not present significant estimates for A1 and A3, while the Logistic, Gompertz and von Bertalanffy models estimate respectively for A1 37.923, 40.801 and 43.159 leaves and 36.606, 38.743 and 39.979 leaves for A3.

For parameters *b* and *c*, divergences between trials and models are observed (Table 2). The Logistic model estimates the largest scale parameters (*b*) and the highest growth rates (*c*), when compared to the other models, for A1 and A2. For A3 Logistic estimated the lowest value of *b* (1.973), and there is no difference between the estimates for *c*.

Table 3 shows the estimates for the parameters adjusted to the number of leaves of the cultivar Nusol 4510, and their respective asymptotic confidence intervals. Similar response to the cultivar Aguará 6 was observed, as for N1 and N3 the Brody model estimated non-significant parameters ($p<0.01$) with high confidence intervals for *a*, and non-zero intervals for *c*.

Considering each of the trial with Nusol 4510 in isolation, no differences were observed between the estimates of the parameter *a* for the Logistic, Gompertz, Brody and von Bertalanffy models(Table 3). The Logistic model, when compared to the others, estimated the highest values of *b* for the three trials, and the highest values of *c* for N1 and N2. For N3 no differences were observed between the estimates of *c* of the different models (Table 3).

For the cultivar Rhino the parameters and confidence intervals are shown in table 4. Again, the Brody model presented non-significant estimates, but this happened only with R2. For R1, R3 and for the fourth situation (All), where mean values of the three trials were used, despite obtaining significant parameters, confidence intervals with greater amplitudes were obtained.

Within each of the trials, it was observed that there are no differences for parameter *a* between the four models. The Logistic model estimated the highest values of *b* and *c* in all trials when compared to the others. In R1 Brody and von Bertalanffy estimated the smallest values for parameter *b*, while the smallest estimate for *c* is given by the Brody model. In R2 there is no difference between Gompertz and von Bertalanffy's estimates for *b* and *c*. In R3 Brody estimated the lowest growth rate and there is no difference between the estimates of *b* given by Gompertz, Brody and von Bertalanffy.

7.4.2 Model selection

As noted in tables 1-4, except for Brody model for A1, A3, N1, N3 and R2 all models fit the data resulting in meaningful parameters. However, the selection of the best model should be made based on quality assessment criteria such as R^2_{adj}, AIC, BIC, IN and PE (Tables 5-7), and on curve-fitting on the data (Figures 1-3).

Sixteen models were generated using the least-squares method (OLS) for each cultivar, considering data obtained from three trials and the fourth situation with the mean of the trials (All). Therefore, a total of 64 models were obtained in order to select the most suitable for each cultivar.

For Aguará 6 cultivar, the lowest value obtained for the R^2_{adj} evaluator was 0.9278 for the Brody model (Table 5). The highest value for this parameter is associated with the Logistics model in the fourth situation (All). Still, even the models that do not present significant parameters, as is the case of the Brody model in A1 and A3 the values of R^2_{adj} are 0.9557 and 0.9407. These results highlight that R^2_{adj} should not be used in isolation to compare models regarding fit and that more than one goodness-of-fit indicator should be used to increase the reliability of model choice.

This same inconsistency in the discriminative capacity of R^2_{adj} has been observed for the cultivars Nusol 4510 and Rhino. The lowest parameter value for the cultivar Nusol 4510 (0.9427) is observed in the third trial and is associated with the Logistic model, while the highest is observed for the estimation using the mean values described by the Gompertz model (0.9935) (Table 6). Even the Brody model in A1 and A3 have R^2_{adj} values of 0.9498 and 0.9575 respectively.

For the Rhino cultivar, the highest R^2_{adj} value is also associated with the Logistic model in the fourth situation (All), being 0.9890 (Table 7). The lowest value for the cultivar was 0.9411 for the Brody model in the third trial. For the second trial, the coefficient value for the Brody model was higher even though the estimated parameters were not significant.

The AIC and BIC fit evaluators, on the other hand, show very consistent results. It was observed that the Brody model presented the highest AIC and BIC values for all generated models (Tables 5-7).

The Logistic model presented the lowest values of AIC and BIC for the four situations simulated with the cultivars Aguará 6 and Rhino, when compared to the other models. For cultivar Aguará 6 the lowest values observed are 31.9437 and 32.7326 for AIC and BIC, respectively (Table 5), and for Rhino the lowest values observed are 38.0122 for AIC and 38.8011 for BIC (Table 7). For both cultivars the lowest values are observed in the fourth situation (All).

Regarding cultivar Nusol 4510 (Table 6), the Logistic model also presented low values for N1, N2 and N3, but the lowest values of AIC and BIC are associated with the Gompertz model for the fourth situation (All), which are 28.1799 and 29.5058, respectively. It was also observed lower values for von Bertalanffy in N2, N3 and All compared to evaluators associated with the logistic model.

Also, although some authors emphasize that IN must be less than 0.3 and PE less than 1, in general, the best model must present the lowest values of IN and PE, as this reflects a good linear approximation (Zeviani et al., 2012). Since IN is inherent to the model, and PE depends on the parameterization used.

Therefore, it was observed that in all situations, the Brody model presented the highest PE values for the adjustments. Table 5 shows the value of 21.4468 for A1, the highest value for this appraiser seen in the study. This implies the fact that the Brody model, in the parameterization used, should not be used to describe the growth of sunflower cultivars in NL. The lowest values of IN and PE are associated with the Logistic and Gompertz models in all situations (Table 5-7), with PE values close to 1 for the von Bertalanffy model in some trials such as in the fourth situation (All) with Aguará 6 (Table 5) and Nusol 4510 (Table 6).

7.4.3 Description of development using number of leaves

The models Logistic, Gompertz and von Bertalanffy, are suitable for describing the development of sunflower plants in NL. Also, based on the largest number of suitable evaluators, it was observed that the best fits are observed in the fourth situation (All) for all cultivars and that the Logistic model is the most suitable for the Aguará 6 cultivars (Table 5; Figure 1a) and Rhino (Table 7; Figure 3a), and the most suitable Gompertz model for the cultivar Nusol 4510 (Table 7; Figure 2b).

The curves fitted by the models on the data confirm the information given by the fit evaluators. The Logistic, Gompertz and von Bertalanffy models have a sigmoid shape and fit the data better, while the Brody model, despite having the curve over the data, overestimates the final NL values for all cultivars (Figures 1-3) and presents deviation from linearity (Tables 5-7).

7.4.4 Critical points

The coordinates of the critical points were obtained using the partial derivatives of the models with better fits for the fourth situation (All) for each cultivar in relation to the independent variable (STa). The inflection point (IP), the point of maximum acceleration (MAP) and deceleration (MDP) and the asymptotic deceleration point (ADP) were determined according to the methodology proposed by Mischan and Pinho et al. (2014).

Figure 4 shows the critical points of the models and situations with the best adjustments for each cultivar. Aguará 6 and Rhino are best described by the Logistic model and Nusol 4510 by the Gompertz model. It is observed that the critical points and the growth pattern of Aguará 6 and Rhino are similar, and the model estimates nearby critical points (Figures 4a and 4c). Whereas, for the cultivar Nusol 4510, the points are given by Gompertz follow another pattern (Figure 4b).

Cultivar Nusol 4510 has MAP and IP before other cultivars. There are differences between Gompertz and Logistic for these points, but the interpretation is the same. For Nusol 4510, MAP is reached around 180 °C accumulated and when the plant has about three expanded leaves (Figure 4b). However, for Aguará 6 and Rhino MAP it is reached around 350 °C accumulated and when the plants have about seven leaves (Figure 4a and 4b).

Therefore, the cultivar Nusol 4510 shows positive and increasing growth before the others. When the IP is reached, the curve concavity changes and the growth rate starts to decrease (Silva, 2020). Observe that Nusol reaches IP around 500 °C and 10 leaves, while Aguará and Rhino reach the point with around 17 leaves and 600 °C accumulated (Figure 4).

Aguará 6 and Rhino reach the MDP when they have around 30 leaves while Nusol 4510 reaches the point with around 20 leaves. Although ADP was observed around 1100 °C accumulated for all cultivars, it was observed that Aguará 6 and Rhino have at the point just over 30 leaves and Nusol 4510 around 25 leaves (Figure 4).

7.5 DISCUSSION

Plant growth and development is complex and involves many processes. Modeling is an indispensable tool to characterize the growth and development of plants, in addition to the study of growth or development curves generate strategies for futures plantings, adapting management (Streck et al., 2008; Mangueira et al., 2016). Several authors have used non-linear models to describe plants growth and development (Jane et al., 2019; Jane et al., 2020a; Mello et al., 2022; Frühauf et al., 2021; Silva et al., 2021).

In this sense, Jane et al. (2020a) evaluated the adjustment of the nonlinear models Logistic, Gompertz, Brody and von Bertalanffy in the growth of stalks of the ratoon cane variety

RB92579, in height and diameter, and did not observe violations in the assumptions of normality, independence and homoscedasticity.

Likewise, Ribeiro et al. (2017), adjusted the Brody, Gompertz, Logístico and von Bertalanffy models in the growth and development of pequi fruits, based on their physical characteristics, such as longitudinal and transversal diameter, and fresh mass obtained over time. The Shapiro-Wilk, Breusch-Pagan and Durbin-Watson tests were used to verify the residuals and violations of the independence assumption were observed.

When the assumptions are violated, the parameters must be estimated using the generalized least squares method (Mangueira et al., 2016; Muniz et al., 2017), adding weights based on the variance and introducing the autocorrelation to the models, in order to minimize the standard error and estimation bias (Guedes et al., 2004; Fernandes et al., 2014).

Despite its limitations, the Logistic model is the most used to describe growth and development curves, being defined as the most suitable for several crops such as cocoa (Muniz et al., 2017) and sugarcane (Jane et al., 2020b). The Gompertz model, on the other hand, does not present symmetrical response, as the inflection point is reached in 37% of the asymptote, and for this reason, it is the most suitable for describing growth in the ratoon cane cycle and coffee fruit (Fernandes et al., 2014; Jane et al. 2020a).

Brody and von Bertalanffy models are also frequently applied to describe growth and development curves. However, in many situations such as those described by Jane et al. (2020a) and Ribeiro et al. (2017), the parameters estimated by the Brody and von Bertalanffy model are not significant or presented confidence intervals with greater amplitude or not different from zero, indicating that the models do not provide a good fit or are not adequate. These results corroborate the present study since the Brody model in some situations did not converge in significant parameters and the von Bertalanffy model presented larger confidence intervals for the parameters.

The model must simulate the observed response therefore, it must present good fit indicators. More than one adjustment indicator should always be used, as according to studies by Sousa et al. (2014) and Mello et al. (2022), use only R^2_{adj}, for example, does not allow differentiating the models, and still, the non-application of other evaluators can lead to the choice of imprecise models that are far from linearity. Therefore, in addition to a high R^2_{adj}, suitable models must have lower AIC and BIC values, and still conventionally lower IN and PE values (Zeviani et al., 2012; Fernandes et al., 2014; Jane et al., 2020a). Therefore, the best model is the one with the best set of suitable evaluators.

The study of crop growth and development patterns, carried out using regression models, helps to identify the morphological differences of plants, quantify production and adapt management to the phenological phases (Fernández-Chuairey et al., 2019). The coordinates of the critical points were proposed by Mischan and Pinho (2014) and numerous authors apply these points to make considerations about plant growth, productivity and management. Carini et al. (2020), used IP, MAP and MDP to make inferences about the growth and response of three lettuce cultivars. In turn, Kleinpaul et al. (2019), in addition to using IP, MAP and MDP, used ADP to describe the accumulation of fresh and dry rye mass.

Mello et al. (2022) defined that the Logistic model is the most adequate to describe the growth curve in height of the sunflower cultivar Rhino and made considerations about the management based on MAP, IP, MDP and ADP. According to the authors, in the initial period, before MAP, plants have less growth capacity and, consequently, greater care should be taken with weed control. Top-dressing fertilizer applications would have optimized results if they were carried out between the MAP and IP range, as in this phase there is greater growth, and ADP can be used as an indicator of growth stabilization and maturity.

In the present study, the cultivars Aguará 6 and Rhino present asymmetrical growth patterns in relation to IP and a higher number of leaves (parameter *a*) in comparison to Nusol

4510. On the other hand, the cultivar Nusol 4510 does not present this pattern because it is better described by the Gompertz model, and most of the time presents a decreasing growth rate, that is, the cultivar has MAP and IP in a period before the others. This result is similar to that observed by Fernandes et al. (2014) when modeling the growth of coffee fruits, as this is characteristic of the Gompertz model.

7.6 CONCLUSIONS

The best fits are observed in situations where the average of the observations of the three trials with each cultivar is used. The Logistic model is the most suitable for the cultivars Aguará 6 and Rhino while for the cultivar Nusol 4510 the Gompertz model is more suitable. The Brody model presented high PE values (PE>1), and in many situations non-significant parameters, therefore it should not be used in the description of NL development of sunflower cultivars. Critical points were defined for the models with the best fit and allow to differentiate cultivars according to the development pattern. Aguará 6 and Rhino reach the inflection point (PI) at 50% of the asymptote, while Nusol 4510 reaches the PI at 37% of the asymptote.

7.7 ACKNOWLEDGEMENTS

To the scholars and volunteers for their help in carrying out experiments and collecting data. To the Federal University of Santa Maria (UFSM), National Council for Scientific and Technological Development (CNPq), Research Support Foundation of the State of Rio Grande do Sul (FAPERGS) and to the Coordination for the Improvement of Higher Education Personnel (CAPES, Brazil - finance code 001) for scholarships. To the FAPERGS/CNPq by financial support (Process number 16/2551-0000257-6 ARD/PPP).

7.8 CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

7.9 REFERENCES

Akaike H. 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control 19:716-23.

Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; Gonçalves, J.L.M.; Sparovek, G. 2013. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift 22: 711-728.

Archontoulis, S.V.; Miguez, F.E. 2015. Nonlinear regression models and applications in agricultural research. Agronomy Journal 107:786-98.

Arnold, C.T. 1959. The determination and significance of the base temperature in a linear heat unit system. Proceedings of the American Society for Horticultural Science 74:430-455.

Bates, D.M.; Watts, D.G. 1988. Regression Analysis and its Applications. New York: John Wiley & Sons, New York, USA, 867 p.

Bem, C.M. de; Cargnelutti Filho, A.; Chaves, G.G.; Kleinpaul, J.A.; Pezzini, RV; Lavezo, A. 2017a. Gompertz and Logistic Models to the Productive Traits of Sunn Hemp. Journal of Agricultural Science 10:225-38.

Bem, C.M. de; Cargnelutti Filho, A.; Facco, G.; Schabarum, D.E.; Silveira, D.L,; Simões, F.M.; Uliana, D.B. 2017b. Growth models for morphological traits of sunn hemp. Semina: Ciências Agrárias 38:2933-43.

Brody, S. 1945. Bioenergetics and Growth. New York: Rheinhold Publishing, 1023p.

Carini, F.; Cargnelutti Filho, A.; Pezzini, R.V.; Souza, J.M. de; Chaves, G.G.; Procedi, A. 2020. Nonlinear models for describing lettuce growth in autumn-winter. Ciência Rural 50: e20190534.

Castro, C.; Leite, R.M.V.B.C. 2018. The oil & protein crop supply chain in South America. Oilseeds fats Crop Lipids 25:1-11.

CQFS - Comissão de Química e Fertilidade do Solo. 2016. Manual of fertilization and liming for the States of Rio Grande do Sul and Santa Catarina. Porto Alegre, Brazil: Sociedade Brasileira de Ciência do Solo.

de La Haba, P.; Amil-Ruiz, F.; Agüera, E. 2020. Physiological and proteomic characterization of the elevated temperature effect on sunflower (Helianthus annuus L.) primary leaves. Russian Journal of Plant Physiology 67:1094-1104.

Fernandes, T.J.; Pereira, A.A.; Muniz, J.A.; Savian, T.V. 2014. Selection of nonlinear models for the description of the growth curves of coffee fruit. Coffee Science. 9:207-215.

Fernández-Chuairey, L.; Oca, LR-M. de; Guerra-Bustillo, C.W.; Pozo-Fernández, M.V.Z.J del. 2019. Statistical-Mathematical Modeling in Agrarian Processes. An application in Agricultural Engineering. Revista Ciências Técnicas Agrícolas 28:e08.

Fonts, C.; Andrade, F.H.; Grondona, M.; Hall, A.; León, A.J. 2008. Phenological characterization of near-isogenic sunflower families bearing two QTLs for photoperiodic response. Crop Science 48:1579-1585.

Frühauf, A.C.; Assis, P.G.; Barbosa, A.C.M.C.; Fernandes, T.J.; Muniz, J.A. 2021. Nonlinear models in the study of the cedar diametric growth in a seasonally dry tropical forest. Revista Brasileira de Ciências Agrárias 15:4-11.

Gilmore, E.C.; Rogers, J.S. 1958. Heat units as a method of measuring maturity in corn. Agronomy Journal 50:611-615.

Goyne, P.J.; Schneiter, A.A. 1987. Photoperiod influence on development in sunflower genotypes. Agronomy Journal 79:704-709.

Guedes, M.H.P; Muniz, J.A.; Perez, J.R.O.; Silva, F.F.; Aquino, L.H. de; Santos, C.L. dos. 2004. Growth functions of Santa Inês and Bergamacy lambs considering heteroscedastic variance. Ciência e Agrotecnologia 28:381-388.

Jane, S.A.; Fernandes, F.A.; Muniz, J.A.; Fernandes, T.J. 2020a. Nonlinear models to describe height and diameter of sugarcane RB92579 variety. Revista Ciência Agronômica 51:e20196660.

Jane, S.A.; Fernandes, F.A.; Silva, E.M.; Muniz J.A.; Fernandes, T.J.; Pimentel, G.V. 2020b. Adjusting the growth curve of sugarcane varieties using nonlinear models. Ciência Rural 50:e20190408.

Jane, S.A.; Fernandes, F.A.; Silva, E.M.; Muniz, J.A.; Fernandes, T.J. 2019. Comparison of polynomial and nonlinear models on description of pepper growth. Revista Brasileira de Ciências Agrárias 14:e7180.

Kaya, Y. 2020. Sunflower production in Blacksea Region: the situation and problems. International Journal of Innovative Approaches in Agricultural Research 4:147-155.

Kleinpaul, J.A.; Cargnelutti Filho, A.; Carini, F.; Pezzini, R.V.; Chaves, G.G.; Thomasi, R.M. 2019. Productive traits of rye cultivars grown under different sowing seasons. Revista Brasileira de Engenharia Agrícola e Ambiental 23:937-44.

Mangueira, R.A.F.; Savian, T.V.; Muniz, J.A.; Sermarini, R.A.; Crosariol Netto, J. 2016. Logistic model considering different error distributions applied in maize height data. Revista Brasileira de Biometria 34:317-333.

Mazucheli, J.; Achcar, J.A. 2002. Considerations about nonlinear regression. Acta Scientiarum. Technology 24:1761-1770.

Mazzini, A,R.A; Muniz, J.A; Aquino, L.H. de; Silva, F.F. 2003. Growth curve analysis for Hereford cattle males. Ciência e Agrotecnologia 27:1105-1112.

Mcmaster, G.S.; Smika, D.E. 1988. Estimation and evaluation of winter wheat phenology in the central Great Plains. Agricultural and Forest Meteorology 43:1-18.

Meade, K.A.; Cooper, M.; Beavis, W.D. 2013. Modeling biomass accumulation in maize kernels. Field Crops Research 151:92-100.

Mello, A.C.; Toebe, M.; Souza, R.R. de; Paraginski, J.A.; Somavilla, J.C.; Martins, V.; Vieira, A.C. 2022. Nonlinear models in the height description of the Rhino sunflower cultivar. Ciência Rural 52:e20210213.

Mischan, M.M.; Pinho, S.Z. 2014. Modelos não lineares: funções assintóticas de crescimento. São Paulo, Brazil: Cultura Acadêmica. 194 p.

Muniz, J.A.; Nascimento, M.D.S.; Fernandes, T.J. 2017. Nonlinear models for description of cacao fruit growth with assumption violations. Revista Caatinga 30:250-257.

Pereira, A.A.; Morais, A.R. de; Scalco, M.S.; Fernandes, T.J. 2014. Description of the vegetative growth of coffee cultivar Rubi MG 1192, using regression models. Coffee Science 9:236-271.

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Regazzi, A.J.; Silva, C.H.O. 2010. Tests for model identity and parameter equality with nonlinear regression models in data from randomized complete block design. Revista Ceres 57:315-320.

Ribeiro, T.D.; Mattos, R.W.P. de; Morais, A.R. de; Muniz, J.A. 2018. Description of the growth of pequi fruits by nonlinear models. Revista Brasileira de Fruticultura 40:e-949.

Ritz,. C; Streibig, J.C. 2008. Nonlinear regression with R. Springer, New York . 142p.

Schneiter, A.A.; Miller, J.F. 1981. Description of Sunflower Growth Stages. Crop Science 21:901-903.

Schwarz, G. (1978). Estimating the Dimension of a Model. The Annals of Statistics, 6:461-464.

Seber, G.A.F.; Lee, A.J. 2003. Linear Regression Analysis. John Wiley, New York, 2ed. 557p.

Seber, G.A.F.; Wild, C.J. 2003. Nonlinear Regression. John Wiley, New York. 768p.

Seiler, G.J.; Gulya, T.J. 2016. Sunflower: Overview, 2nd ed, Encyclopedia of Food Grains: Second Edition. Elsevier Ltda, p. 247-253.

Sentelhas, P.C.; Nogueira, S. dos S.S.; Júnior, M.J.P.; Santos, R.R. dos. 1994. Base-temperature and degree-days to cultivars of sunflower. Revista Brasileira de Agrometeorologia 2:43-49.

Silva, É.M.; Fruhauf, A.C.; Silva, J.A.M.; Fernandes, T.J.; Silva, V.F. 2021. Evaluation of the critical points of the most adequate nonlinear model in adjusting growth data of ‘green dwarf’ coconut fruits. Revista Brasileira de Fruticultura 43:1-11.

Silva, É.M.; Tadeu, M.H.; Silva, V.F.; Pio, R.; Fernandes, T.J.; Muniz, J.A.. 2020. Description of blackberry fruit growth by nonlinear regression models. Revista Brasileira de Fruticultura 42:1-8.

Sousa, I.F.; Neto, J.E.K.; Muniz, J.A.; Guimarães, R.M.; Savian, T.V.; Muniz, F.R. 2014. Fitting nonlinear autoregressive models to describe coffee seed germination. Ciência Rural 44:2016-2021.

Streck, N.A.; Bosco, L.C.; Lucas, D.D.P; Lago, I. 2008. Modeling leaf appearance in cultivated rice and red rice. Pesquisa Agropecuária Brasileira 43:559-567.

Tholon, P.; Queiroz, S. 2007. Models for the analysis of growth curves for rearing tinamous (Rhynchotus rufescens) in captivity. Brazilian Journal of Poultry Science 9:1806-9061.

USDA. Foreign Agricultural Service. 2021. Oilseeds: world market and trade. March 2021. 39p.

Villalobos, F.J.; Hall, A.J.; Ritchie, J.T.; Orgaz, F. 1996. Oilcrop-Sun: A development, growth, and yield model of the sunflower crop. Agronomy Journal 88:403-415.

Wang, Y. 2012. Gauss-Newton method. Wiley Interdisciplinary Reviews: Computational Statistics, 4: 415-420.

Wheeler, M.W.; Park, R.M.; Bailer, A.J. 2006. Comparing median lethal concentration values using confidence interval overlap or ratio tests. Environmental Toxicology and Chemistry 25:441-1444.

Wickham, H. 2016. Ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

Zeileis, A.; Hothorn, T. 2002. Diagnostic Checking in Regression Relationships. R News 2:7-10.

Zeviani, W.M.; Silva, C.A.; Carneiro, W.J.O.; Muniz, J.A. 2012. Non linear models to potassium release from animals manure in Latosols. Ciência Rural 42:1789-1796.

7.10 TABLES

Table 1

P-value of the Shapiro-Wilk (SW), Durbin-Watson (DW) and Breusch-Pagan (BP) tests, applied to the residues of the Logistic, Gompertz, Brody and von Bertalanffy models, adjusted to the number of leaves of sunflower cultivars.

		Aguará 6			Nusol 4510			Rhino		
Trial	Model	SW	DW	BP	SW	DW	BP	SW	DW	BP
First	Logistic	0.8108	0.5900	0.1256	0.8925	0.4520	0.0556	0.5130	0.5340	0.0942
	Gompertz	0.2173	0.4500	0.2148	0.7232	0.3560	0.0565	0.3354	0.8280	0.1394
	Brody	0.2156	0.1680	0.4422	0.6380	0.1540	0.0978	0.2112	0.3240	0.7624
	von Bertalanffy	0.3507	0.3000	0.2839	0.8482	0.3240	0.0643	0.4728	0.8120	0.1900
Second	Logistic	0.9426	0.6760	0.4577	0.3028	0.9160	0.3413	0.5863	0.2880	0.2364
	Gompertz	0.9304	0.5080	0.8924	0.2943	0.3560	0.6212	0.3560	0.1300	0.2129
	Brody	0.7926	0.0720	0.8730	0.6094	0.0200	0.7608	0.9865	0.0260	0.2661
	von Bertalanffy	0.7961	0.3640	0.9740	0.5059	0.2060	0.6808	0.8358	0.0800	0.2199
Third	Logistic	0.5389	0.7420	0.3449	0.1648	0.1640	0.7017	0.5597	0.6380	0.0727
	Gompertz	0.4189	0.7840	0.4475	0.4102	0.3000	0.3909	0.6751	0.2940	0.1359
	Brody	0.2989	1.0000	0.4665	0.5846	0.7620	0.4876	0.2804	0.0580	0.3605
	von Bertalanffy	0.3235	0.8540	0.4620	0.4996	0.3880	0.3437	0.4984	0.2140	0.1822
All	Logistic	0.6561	0.1300	0.4734	0.3863	0.1260	0.6446	0.4052	0.4100	0.2402
	Gompertz	0.9753	0.0240	0.4210	0.5849	0.5160	0.0828	0.4161	0.1340	0.1400
	Brody	0.7265	0.0300	0.3231	0.6657	0.1980	0.0312	0.7956	0.0160	0.2242
	von Bertalanffy	0.8683	0.0800	0.3708	0.8974	0.5140	0.0390	0.7341	0.0580	0.1264

Table 2

Estimates for the parameters *a*, *b* and *c*, lower limit (LL) and upper limit (UL) of the confidence interval ($CI_{95\%}$), of Logistic, Gompertz, Brody and von Bertalanffy models adjusted to the number of leaves in sunflower plants of Aguará 6 cultivar.

Trial	Logistic			Gompertz			Brody			von Bertalanffy		
First	LL	Mean	UL	LL	Mean	UL	LL	Mean	UL	LL	Mean	UL
a	32.923	$37.923^{aA(1)}$	42.924	32.438	40.801^{aA}	49.165	9.897	61.811^{ns}	113.725	31.502	43.159^{aA}	54.816
b	2.368	3.282^{aA}	4.196	1.077	1.672^{aB}	2.266	0.842	1.172^{ns}	1.503	0.533	1.059^{aC}	1.585
c	0.0034	0.0051^{bA}	0.0068	0.0017	0.0031^{abB}	0.0045	-0.0003	0.0009^{ns}	0.0020	0.0011	0.0024^{abB}	0.0037
Second												
a	28.528	30.887^{bA}	33.246	27.955	31.736^{bA}	35.516	22.859	37.593^{A}	52.327	27.397	32.250^{aA}	37.104
b	2.712	3.964^{aA}	5.217	1.152	2.111^{aB}	3.071	0.836	1.323^{B}	1.810	0.168	1.599^{aB}	3.030
c	0.0052	0.0078^{aA}	0.0104	0.0027	0.0050^{aB}	0.0072	0.0002	0.0018^{C}	0.0033	0.0019	0.0041^{aB}	0.0063
Third												
a	30.392	36.606^{abA}	42.820	29.343	38.743^{abA}	48.144	24.151	44.433^{ns}	64.715	28.532	39.979^{aA}	51.427
b	1.159	1.973^{bA}	2.787	0.458	0.977^{bB}	1.496	0.763	1.096^{ns}	1.428	0.367	0.651^{aB}	0.935
c	0.0016	0.0033^{cA}	0.0049	0.0008	0.0021^{bA}	0.0035	-0.0001	0.0011^{ns}	0.0022	0.0005	0.0018^{bA}	0.0031
All												
a	32.824	34.774	36.723	33.024	36.816	40.608	30.136	45.504	60.872	32.941	38.275	43.609
b	2.429	2.877	3.324	1.109	1.453	1.796	0.950	1.204	1.458	0.637	0.914	1.190
c	0.0040	0.0049	0.0058	0.0022	0.0030	0.0039	0.0006	0.0012	0.0020	0.0016	0.0024	0.0033

(1) Comparison of parameter estimates (*a*, *b* and *c*) between trials and between models. Averages followed by the same lowercase letter do not differ between trials for the same model. Averages followed by the same capital letter do not differ for the same trial between models. ^{ns} non-significant , i.e.

Table 3

Estimates for the parameters *a*, *b* and *c*, lower limit (LL) and upper limit (UL) of the confidence interval ($CI_{95\%}$), of Logistic, Gompertz, Brody and von Bertalanffy models adjusted to the number of leaves in sunflower plants of Nusol 4510 cultivar.

Trial	Logistic			Gompertz			Brody			von Bertalanffy		
First	LL	Mean	UL	LL	Mean	UL	LL	Mean	UL	LL	Mean	UL
a	27.348	$31.682^{aA(1)}$	36.015	26.913	33.454^{aA}	39.996	18.688	43.48^{ns}	68.273	26.331	34.822^{aA}	43.313
b	2.163	3.219^{abA}	4.275	0.996	1.682^{abB}	2.368	0.842	1.254^{ns}	1.667	0.467	1.094^{aB}	1.720
c	0.0032	0.0053^{abA}	0.0073	0.0017	0.0033^{abAB}	0.0050	-0.0001	0.0012^{ns}	0.0024	0.0012	0.0027^{abB}	0.0042
Second												
a	25.543	27.193^{bA}	28.843	25.354	28.123^{aA}	30.892	22.549	33.325^{A}	44.101	25.087	28.812^{aA}	32.538
b	2.716	3.565^{aA}	4.414	1.213	1.849^{aB}	2.485	0.915	1.289^{B}	1.663	0.540	1.238^{aB}	1.935
c	0.0054	0.0072^{aA}	0.0090	0.0029	0.0045^{aB}	0.0061	0.0005	0.0017^{C}	0.0030	0.0021	0.0036^{aB}	0.0052
Third												
a	24.068	31.563^{abA}	39.058	23.799	33.415^{aA}	43.031	15.620	44.760^{ns}	73.905	23.419	34.876^{aA}	46.333
b	1.471	2.387^{bA}	3.303	0.697	1.200^{bB}	1.704	0.896	1.089^{ns}	1.283	0.467	0.760^{aB}	1.053
c	0.0019	0.0039^{bA}	0.0060	0.0010	0.0025^{bA}	0.0040	-0.0001	0.0009^{ns}	0.0019	0.0007	0.0020^{bA}	0.0034
All												
a	27.486	29.479	31.472	28.716	31.015	33.314	28.649	39.298	49.947	29.184	32.169	35.154
b	2.410	2.937	3.464	1.267	1.530	1.793	1.022	1.202	1.382	0.762	0.977	1.191
c	0.0042	0.0053	0.0064	0.0027	0.0034	0.0041	0.0006	0.0013	0.0019	0.0021	0.0027	0.0034

(1) Comparison of parameter estimates (*a*, *b* and *c*) between trials and between models. Averages followed by the same lowercase letter do not differ between trials for the same model. Averages followed by the same capital letter do not differ for the same trial between models. ^{ns} non-significant , i.e.

Table 4

Estimates for the parameters *a*, *b* and *c*, lower limit (LL) and upper limit (UL) of the confidence interval (CI$_{95\%}$), of Logistic, Gompertz, Brody and von Bertalanffy models adjusted to the number of leaves in sunflower plants of Rhino cultivar.

Trial	Logistic			Gompertz			Brody			von Bertalanffy		
First	LL	Mean	UL	LL	Mean	UL	LL	Mean	UL	LL	Mean	UL
a	34.616	38.022^{aA}(1)	41.429	34.916	40.549^{aA}	46.181	23.234	59.250^{aA}	95.266	34.663	42.419^{aA}	50.174
b	2.543	3.328^{aA}	4.114	1.188	1.673^{aB}	2.159	0.919	1.163^{aC}	1.406	0.627	1.070^{aC}	1.513
c	0.0043	0.0060^{aA}	0.0076	0.0024	0.0036^{aB}	0.0049	0.0001	0.0010^{aC}	0.0020	0.0016	0.0028^{aB}	0.0040
Second												
a	34.096	37.409^{aA}	40.722	33.916	39.168^{abA}	44.420	20.791	55.769^{ns}	90.747	33.267	40.299^{aA}	47.330
b	2.592	3.551^{aA}	4.510	1.214	1.892^{aB}	2.571	0.875	1.1966^{ns}	1.517	0.475	1.341^{aB}	2.207
c	0.0044	0.0062^{aA}	0.0081	0.0024	0.0040^{aB}	0.0055	-0.0001	0.0011^{ns}	0.0023	0.0017	0.0033^{aB}	0.0048
Third												
a	30.573	33.514^{bA}	36.454	30.334	34.653^{bA}	38.971	26.129	40.650^{aA}	55.172	29.902	35.457^{aA}	41.013
b	2.598	3.768^{aA}	4.939	1.233	2.062^{aB}	2.890	0.855	1.442^{aB}	2.030	0.395	1.507^{aB}	2.618
c	0.0046	0.0069^{aA}	0.0092	0.0026	0.0045^{aB}	0.0064	0.0003	0.0018^{aC}	0.0032	0.0019	0.0037^{aB}	0.0055
All												
a	33.757	36.201	38.644	33.890	37.843	41.797	27.324	49.834	72.345	33.565	39.034	44.502
b	2.795	3.521	4.248	1.346	1.869	2.391	0.922	1.251	1.580	0.656	1.284	1.911
c	0.0049	0.0063	0.0078	0.0028	0.0040	0.0053	0.0002	0.0013	0.0024	0.0020	0.0033	0.0045

(1)Comparison of parameter estimates (*a*, *b* and *c*) between trials and between models. Averages followed by the same lowercase letter do not differ between trials for the same model. Averages followed by the same capital letter do not differ for the same trial between models. ^{ns} non-significant , i.e.

Table 5

Quality of fit evaluation criteria for the Logistic, Gompertz, Brody and von Bertalanffy models, adjusted to the number of leaves of the cultivar Aguará 6 sunflower plants. Adjusted coefficient of determination (R^2_{adj}), Akaike information criterion (AIC), Bayesian information criterion (BIC), intrinsic curvature measurements (IN) and parameter effect curvature measurements (PE).

Trial	Model	R^2_{adj}	AIC	BIC	PE	IN
First	Logistic	0.9750	44.9371	45.7260	1.3717	0.2513
	Gompertz	0.9714	46.1773	46.9662	2.5960	0.2559
	Brody	0.9557	50.0861	50.8750	21.4468	0.1977
	von Bertalanffy	0.9684	47.1015	47.8904	3.4674	0.2759
Second	Logistic	0.9791	41.8106	42.5995	0.7408	0.2953
	Gompertz	0.9675	46.0367	46.8256	1.3391	0.4922
	Brody	0.9278	52.8039	53.5928	5.5012	0.2531
	von Bertalanffy	0.9606	47.8984	48.6873	3.2617	1.0020
Third	Logistic	0.9421	48.0440	48.8329	2.1893	0.2615
	Gompertz	0.9414	48.1562	48.9451	3.7842	0.2213
	Brody	0.9407	48.2663	49.0552	10.1762	0.2028
	von Bertalanffy	0.9412	48.1923	48.9812	4.5866	0.2095
All	Logistic	0.9924	31.9437	32.7326	0.5887	0.1233
	Gompertz	0.9872	36.6818	37.4707	1.2908	0.1366
	Brody	0.9744	42.8656	43.6545	6.4656	0.1426
	von Bertalanffy	0.9840	38.6665	39.4554	1.8010	0.1375

Table 6

Quality of fit evaluation criteria for the Logistic, Gompertz, Brody and von Bertalanffy models, adjusted to the number of leaves of the cultivar Nusol 4510 sunflower plants. Adjusted coefficient of determination (R^2_{adj}), Akaike information criterion (AIC), Bayesian information criterion (BIC), intrinsic curvature measurements (IN) and parameter effect curvature measurements (PE).

Trial	Model	R^2_{adj}	AIC	BIC	PE	IN
First	Logistic	0.9670	44.3885	45.1774	1.4389	0.2942
	Gompertz	0.9640	45.1734	45.9623	2.4289	0.2882
	Brody	0.9498	48.1514	48.9403	11.0079	0.2172
	von Bertalanffy	0.9613	45.8279	46.6168	3.1336	0.3001
Second	Logistic	0.9868	34.7191	35.5080	0.5855	0.2120
	Gompertz	0.9787	39.1570	39.9459	1.1044	0.3127
	Brody	0.9517	46.2859	47.0748	4.7258	0.2036
	von Bertalanffy	0.9732	41.2438	42.0327	2.0672	0.4648
Third	Logistic	0.9427	48.7676	49.5565	2.4678	0.3608
	Gompertz	0.9520	47.0820	47.8709	3.6300	0.2852
	Brody	0.9575	45.9286	46.7175	14.3206	0.2041
	von Bertalanffy	0.9550	46.4591	47.2480	4.3521	0.2631
All	Logistic	0.9907	32.2727	33.0616	0.7009	0.1617
	Gompertz	0.9935	28.7199	29.5088	0.8919	0.1242
	Brody	0.9845	36.5585	37.3474	4.8644	0.1200
	von Bertalanffy	0.9928	29.6390	30.4279	1.1691	0.1328

Table 7

Quality of fit evaluation criteria for the Logistic, Gompertz, Brody and von Bertalanffy models, adjusted to the number of leaves of the cultivar Rhino sunflower plants. Adjusted coefficient of determination (R^2_{adj}), Akaike information criterion (AIC), Bayesian information criterion (BIC), intrinsic curvature measurements (IN) and parameter effect curvature measurements (PE).

Trial	Model	R^2_{adj}	AIC	BIC	PE	IN
First	Logistic	0.9850	41.7496	42.5385	0.9400	0.2181
	Gompertz	0.9830	42.8824	43.6713	1.7513	0.2506
	Brody	0.9685	48.4371	49.2260	13.8871	0.1711
	von Bertalanffy	0.9810	43.9165	44.7054	2.4268	0.3475
Second	Logistic	0.9820	43.0328	43.8217	0.9382	0.2446
	Gompertz	0.9785	44.7492	45.5381	1.7207	0.3708
	Brody	0.9527	51.7335	52.5224	13.0403	0.1965
	von Bertalanffy	0.9754	46.1427	46.9316	2.8633	0.7700
Third	Logistic	0.9760	43.5794	44.3683	0.9208	0.2959
	Gompertz	0.9698	45.7524	46.5413	1.4742	0.3618
	Brody	0.9411	51.6556	52.4445	5.1038	0.2488
	von Bertalanffy	0.9645	47.2816	48.0705	2.8341	0.5019
All	Logistic	0.9890	38.0122	38.8011	0.7019	0.1908
	Gompertz	0.9856	40.5267	41.3156	1.2880	0.2603
	Brody	0.9624	49.0493	49.8382	8.2211	0.1858
	von Bertalanffy	0.9822	42.5566	43.3455	2.1224	0.4399

7.11 FIGURES

FIGURE LEGENDS

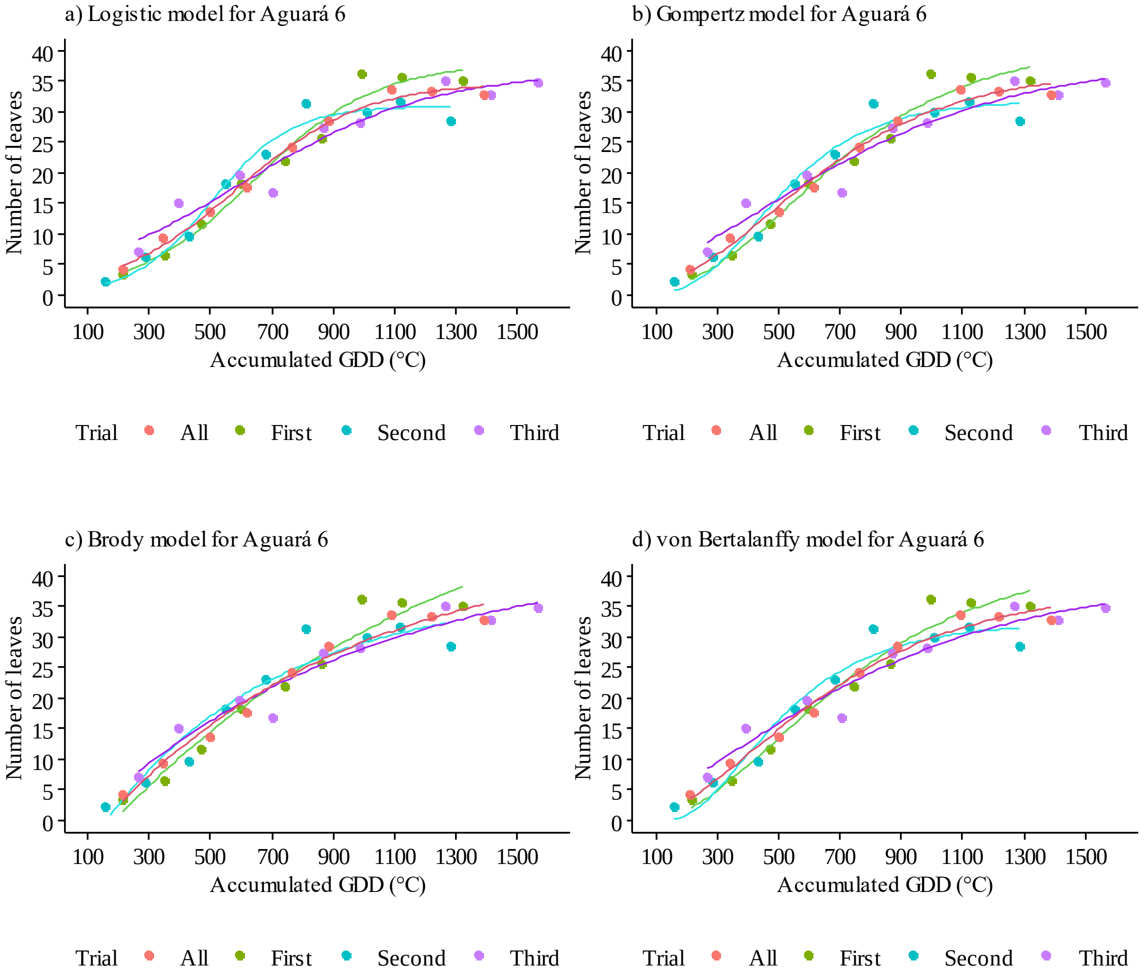
FIGURE 1 – Adjustment of the Logistic, Gompertz, Brody and von Bertalanffy models to the number of leaves data of sunflower cultivar Aguará 6 as a function of the accumulated growing degree days (GDD).

FIGURE 2 – Adjustment of the Logistic, Gompertz, Brody and von Bertalanffy models to the number of leaves data of sunflower cultivar Nusol 4510 as a function of the accumulated growing degree days (GDD).

FIGURE 3 – Adjustment of the Logistic, Gompertz, Brody and von Bertalanffy models to the number of leaves data of sunflower cultivar Rhino as a function of the accumulated growing degree days (GDD).

FIGURE 4 – Adjustment of the best models and their respective critical points for cultivars Aguará 6, Nusol 4510 and Rhino. ADP – Asymptotic deceleration point. IP – Inflection point. MAP – maximum deceleration point. ADP – maximum acceleration point. GDD – growing degree days.

FIGURES

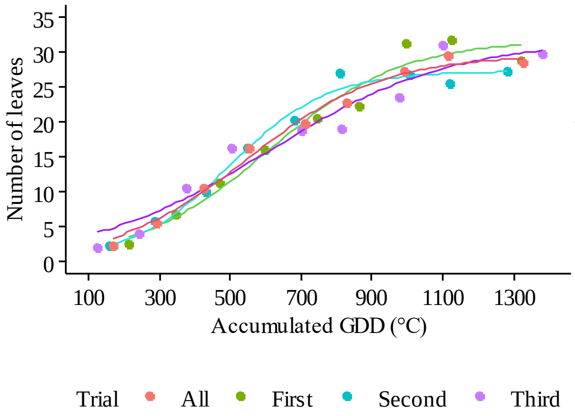


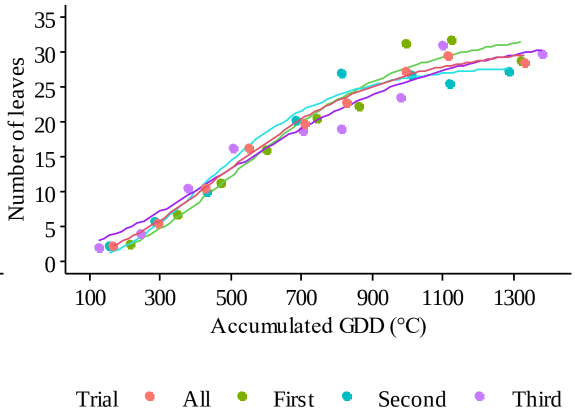
a) Logistic model for Aguará 6

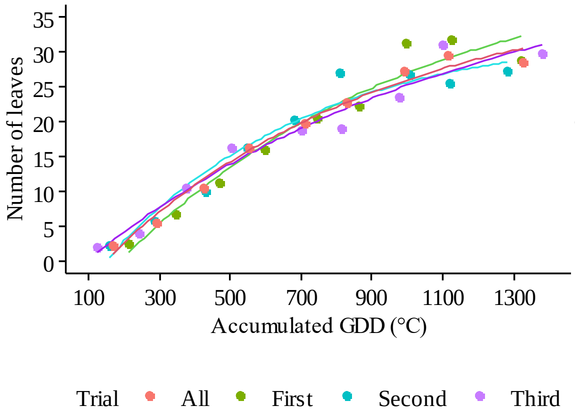
b) Gompertz model for Aguará 6

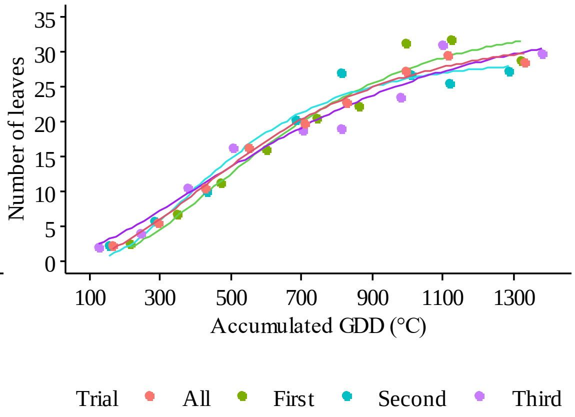
c) Brody model for Aguará 6

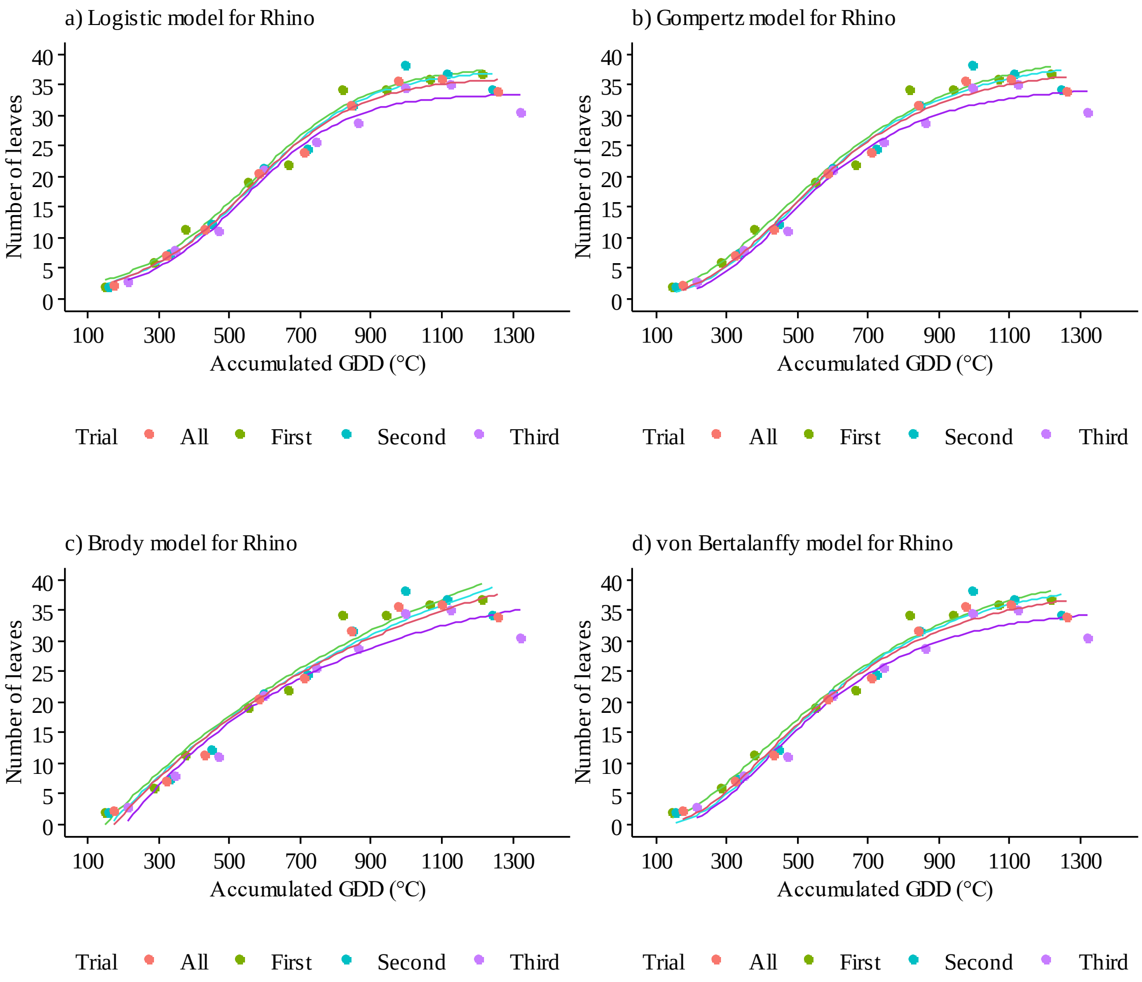
d) von Bertalanffy model for Aguará 6

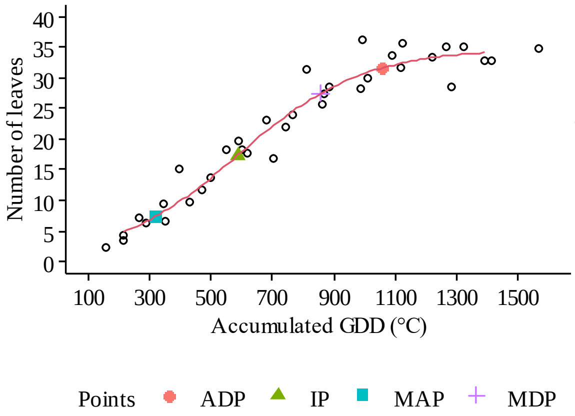

a) Logistic model for Nusol 4510

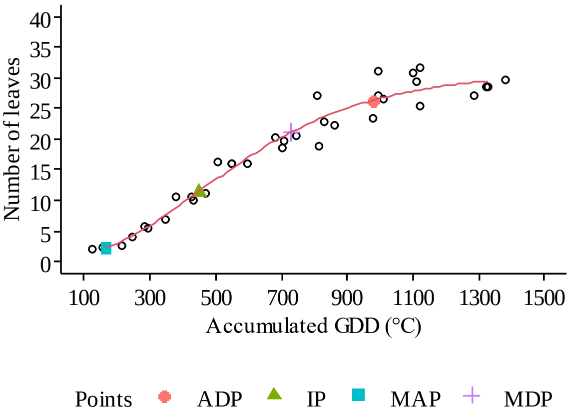

b) Gompertz model for Nusol 4510

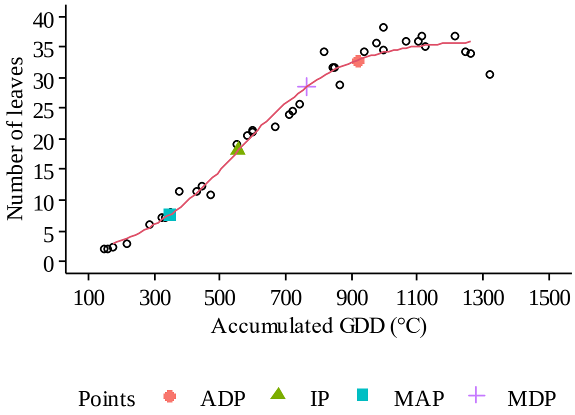

c) Brody model for Nusol 4510


d) von Bertalanffy model for Nusol 4510


a) Logistic model for Rhino
b) Gompertz model for Rhino
c) Brody model for Rhino
d) von Bertalanffy model for Rhino
Number of leaves
0
5
10
15
20
25
30
35
40
100
300
500
700
900
1100
1300
Accumulated GDD (°C)
Trial
All
First
Second
Third


a) Critical points for Logistic Model - Aguará 6


b) Critical points for Gompertz Model - Nusol 4510


c) Critical points for Logistic Model - Rhino

8. CONSIDERAÇÕES FINAIS

Modelos não lineares podem ser usados para descrição do crescimento e desenvolvimento de cultivares de girassol utilizando os caracteres altura, massa fresca de plantas e número de folhas. Os parâmetros estimados fornecem informações práticas e com interpretação biológica servindo para comparação das cultivares e modelos.

O modelo Logístico é o mais adequado para a descrição do crescimento da cultivar de girassol Rhino em altura. Os pontos críticos estimados fornecem informações importantes para o manejo da cultura. As plantas daninhas devem ser controladas até o ponto de máxima aceleração. As aplicações de fertilizantes em cobertura devem ser realizadas entre os pontos de máxima aceleração e o de inflexão. O ponto de desaceleração assintótica é um indicador de maturidade, após atingir este ponto as plantas podem ser colhidas para a produção de silagem sem perda de volume.

Os modelos Logístico e Gompertz descrevem de forma adequada o crescimento em massa de plantas de girassol. Ambos os modelos convergem em estimativas de parâmetros com interpretações práticas e biológicas. Considerar a necessidade do atendimento das pressuposições e inserir a estrutura potência aos modelos resultam em melhor ajuste aos dados. O modelo Logístico é o mais adequado para a descrição do crescimento em massa das cultivares Aguará 6 e Nusol 4510, enquanto Gompertz é o mais adequado para cultivar de girassol Rhino.

Os modelos Logístico, Gompertz e von Bertalanffy podem ser utilizados para a descrição do desenvolvimento de cultivares de girassol em número de folhas. O modelo Logístico é o mais adequado para as cultivares Aguará 6 e Rhino enquanto para a cultivar Nusol 4510 o modelo Gompertz é o mais adequado. O modelo Brody não apresenta padrão sigmoide e não se ajusta para a descrição do desenvolvimento em número de folhas de cultivares de girassol.

Mais estudos devem ser realizados com a cultura, considerando outros caracteres, cultivares, épocas e condições edafoclimáticas. Ainda, outros modelos disponíveis na literatura podem ser utilizados e a metodologia apresentada pode ser aplicada para a descrição do crescimento e desenvolvimento de outras culturas.

9. REFERÊNCIAS BIBLIOGRÁFICAS

AMORIM, D. S.; EDVAN, R. L.; NASCIMENTO, R. R.; BEZERRA, L. R.; ARAÚJO, M. J.; SILVA, A. L.; MIELEZRSKI, F.; NASCIMENTO, K. S. Fermentation profile and nutritional value of sesame silage compared to usual silages. **Italian Journal of Animal Science**, v. 19, n. 1, p. 230-239, 2020.

ARCHONTOULIS, S. V.; MIGUEZ, F. E. Nonlinear regression models and applications in agricultural research. **Agronomy Journal**, v. 107, n. 2, p. 786-798, 2015.

BEM, C. M. de; CARGNELUTTI FILHO, A.; FACCO, G.; SCHABARUM, D. E.; SILVEIRA, D. L.; SIMÕES, F. M.; ULIANA, D. B. Growth models for morphological traits of sunn hemp. **Semina: Ciências Agrarias**. v. 38, n. 2, p. 2933-2943, 2017.

CARINI, F.; CARGNELUTTI FILHO, A.; PEZZINI, R. V.; SOUZA, J. M.; CHAVES, G. G.; PROCEDI, A. Nonlinear models for describing lettuce growth in autumn-winter. **Ciência Rural**, v. 50, n. 7, p. e20190534, 2020.

CASTRO, C.; LEITE, R. M. V. B. C. The oil & protein crop supply chain in South America. **Oilseeds & fats Crops and Lipids**, n. 25, v. 1, p. 1-11, 2018.

FERNANDES, T. J.; PEREIRA, A. A.; MUNIZ, J. A.; SAVIAN, T. V. Selection of nonlinear models for the description of the growth curves of coffee fruit. **Coffee Science**, v. 9, n. 2, p. 207-215, 2014.

FRÜHAUF, A. C.; ASSIS-PEREIRA, G.; BARBOSA, A. C. M. C.; FERNANDES, T. J.; MUNIZ, J. A. Nonlinear models in the study of the cedar diametric growth in a seasonally dry tropical forest. **Revista Brasileira de Ciências Agrárias**, v. 15, n. 4, p 4-11, 2021.

GRATTON, S.; LAWLESS, A. S.; NICHOLS, N. K. Approximate Gauss-newton methods for nonlinear least squares problems. **SIAM Journal on Optimization**, v. 18, n. 1, p. 106-132, 2007.

GUEDES, M. H. P.; MUNIZ, J. A.; PEREZ, J. R. O.; SILVA, F. F.; AQUINO, L. H.; SANTOS, C. L. Growth functions of Santa Inês and Bergamacy lambs considering heteroscedastic variance. **Ciência e Agrotecnologia**, v. 28, n. 2, p. 381-388, 2004.

HESAMI, S. M.; ZILOUEIA, H.; KARIMIAB, K.; ASADINEZHADA, A. Enhanced biogas production from sunflower stalks using hydrothermal and organosolv pretreatment. **Industrial Crops and Products**, v. 76, p. 449-455, 2015.

HLADNI N.; JOCIĆ, S.; MIKLIČ, V.; SAFTIĆ-PANKOVIĆ, D.; KRALJEVIĆ-BALALIĆ, M. Interdependence of yield and yield components of confectionary sunflower hybrids. **Genetika**, v. 43, n. 3, p. 583-594, 2011.

IRAM, S.; TARIQ, I.; AHMAD, K. S.; JAFFRI, S. B. *Helianthus annuus* based biodiesel production from seed oil garnered from a phytoremediated terrain. **International Journal of Ambient Energy**, v. 41, n. 1, p. 1-9, 2020.

JANE, S. A.; FERNANDES, F. A.; MUNIZ, J. A.; FERNANDES, T. J. Nonlinear models to describe height and diameter of sugarcane RB92579 variety. **Revista Ciência Agronômica**, v. 51, n. 4, p. 1-7, 2020.

KAYA, Y. Sunflower Production in Blacksea Region: The Situation and Problems. **International Journal of Innovative Approaches in Agricultural Research**, v. 4, n. 1, p. 147-155, 2020.

KLEINPAUL, J. A.; CARGNELUTTI FILHO, A.; CARINI, F.; PEZZINI, R.V.; CHAVES, G. G.; THOMASI, R. M. Productive traits of rye cultivars grown under different sowing seasons. **Revista Brasileira de Engehnaria Agricola e Ambiental**, v. 23, n. 12, p. 937-944, 2019.

KOUTROUBAS, S. D.; ANTONIADIS, V.; DAMALAS, C. A.; FOTIADIS, S. Sunflower growth and yield response to sewage sludge application under contrasting water availability conditions. **Industrial Crops and Products**, v. 154, p. 112670, 2020.

MANGUEIRA; R. A. F.; SAVIAN, T. V.; MUNIZ, J. A.; SERMARINI, R. A.; CROSARIOL NETTO, J. Logistic model considering different error distributions applied in maize height data. **Revista Brasileira de Biometria**, v. 34, n. 2, p. 317-333, 2016.

MAZUCHELI, J.; ACHCAR, J. A. Considerations about nonlinear regression. **Acta Scientiarum Technology**, v. 24, n. 6, p. 1761-1770, 2002.

MAZZINI, A. R. A.; MUNIZ, J. A.; SILVA, F. F.; AQUINO, L. H. Growth curve for hereford males: heterocedasticity and autoregressives residuals. **Ciência Rural**, v. 35, n. 2, p. 422-427, 2005.

MISCHAN, M. M.; PINHO, S. Z.; CARVALHO, L. R. de. Determination of a point sufficiently close to the asymptote in nonlinear growth functions. **Scientia Agricola**, v. 68, n. 1, p. 109-114, 2011.

MUIANGA, C. A.; MUNIZ, J. A.; FERNANDES, T. J.; SAVIAN, T. V. Description of the growth curve of cashew fruits in nonlinear models. **Revista Brasileira de Fruticultura,** v. 38, n. 1, p. 22-32, 2016.

MUNIZ, J. A.; NASCIMENTO, M. S.; FERNANDES, T. J. Nonlinear models for description of cacao fruit growth with assumption violations. **Revista Caatinga**, v. 30, n. 1, p. 250-257, 2017.

PEREIRA, J. M.; MUNIZ, J. A.; SILVA, C. A. Nonlinear models to predict nitrogen mineralization in an Oxisol. **Scientia Agricola**, v. 62, n. 2, p. 395-400, 2005.

REGAZZI, A. J.; SILVA, C.H.O. Tests for model identity and parameter equality with nonlinear regression models in data from randomized complete block design. **Revista Ceres**, v. 57, n. 3, p. 315-320, 2010.

SEILER, G. J.; GULYA, T.J. **Sunflower: Overview**. Encyclopedia of Food Grains: Second Edition. Elsevier Ltd. 2016.

SILVA, É. M.; FRUHAUF, A. C.; SILVA, E. M.; MUNIZ, J. A.; FERNANDES, T. J.; SILVA, V. F. Evaluation of the critical points of the most adequate nonlinear model in adjusting growth data of ‘green dwarf’ coconut fruits. **Revista Brasileira de Fruticultura**, v. 43, n. 1, p. 1-11, 2021.

SILVA, É. M.; TADEU, M. H.; SILVA, V. F.; PIO, R.; FERNANDES, T. J.; MUNIZ, A. Description of blackberry fruit growth by nonlinear regression models. **Revista Brasileira de Fruticultura**, v. 42, n. 2, p. 1-8, 2020.

SOUSA, I. F.; NETO, J. E. K.; MUNIZ, J.A.; GUIMARÃES, R. M.; SAVIAN, T. V.; MUNIZ, F. R. Fitting nonlinear autoregressive models to describe coffee seed germination. **Ciência Rural**, v. 44, n. 11, p. 2016-2021, 2014.

STRECK, N. A.; BOSCO, L. C.; LUCAS, D. D. P.; LAGO, I. Modeling leaf appearance in cultivated rice and red rice. **Pesquisa Agropecuária Brasileira**, v. 43, n. 5, p 559-567, 2008.

USDAa. Foreign Agricultural Service, 2021. **Oilseeds: world market and trade**. March 2021. 39p.

USDAb. Foreign Agricultural Service, 2021. **World Agricultural Production**. March 2021. 40p.