KSÜ Tarım ve Doğa Derg 27 (4), 994-1004, 2024
KSU J. Agric Nat 27 (4), 994-1004, 2024
DOI:10.18016/ksutarimdoga.vi.1310574

Investigation of Plant Height, Fresh Weight and Dry Weight of Sorghum with Growth Curve Models

Şenol ÇELİK[1]✉, Erdal GÖNÜLAL[2], Halit TUTAR[3]

[1]Department of Animal Sciences, Biometry and Genetics, Faculty of Agriculture, University of Bingol, Bingol, 12000, Türkiye, [2]Bahri Dağdaş International Agricultural Research Institute, Konya, 42000, Türkiye, [3]Department of Plant and Animal Production, Vocational School of Food, Agriculture and Livestock, University of Bingol, Bingöl, 12000, Türkiye

[1]https://orcid.org/0000-0001-5894-8986, [2]https://orcid.org/0000-0002-1621-0892, [3]https://orcid.org/0000-0002-9341-3503

✉: senolcelik@bingol.edu.tr

ABSTRACT

In this study, the sorghum plant, which is one of the most important plants in the world, was used as material. It was grown in Konya province of Türkiye, which has semi-arid climate conditions. Plant height, fresh weight, and dry weight were determined for 11 weeks during the vegetation period. To determine the shape of the plant growth, some growth models were used and the parameters of the models were tried to be defined. The coefficient of determination (R^2), Pseudo R^2, Mean Squares of Error (MSE), and Akaike Information Criteria (AIC) statistics were taken into account in comparing the performances of the Brody, Gompertz, Von Bertalanffy, Logistic, and Log-Logistic models. The R^2, Pseudo R^2, MSE and AIC values of the Gompertz model found suitable for plant height were found to be 0.998, 0.999, 23.162, and 21.013 respectively. The R^2, Pseudo R^2, MSE, and AIC values of the von Bertalanffy model, which was found suitable for wet weight estimation, were obtained as 0.995, 0.998, 1817.141, and 41.993 respectively. The R^2, Pseudo R^2, MSE, and AIC values of the Log-logistic model, which were found suitable for estimating the dry weight of the plant, were calculated as 0.998, 0.9993, 51.007, and 24.784 respectively. It can be suggested that nonlinear mathematical growth models are useful methods in terms of describing important plant characteristics such as plant height, and fresh and dry weight, calculating maximum plant height and weight, and determining the average growth rate. As a result, the growth curve models showed different results in different characteristics such as plant height, and fresh and dry weight of the plant.

Biometrics

Research Article

Article History
Received : 07.06.2023
Accepted : 19.10.2023

Keywords
Growth curve models
Maturing index
Inflection point
Sorghum
Plant Characteristics

Sorgumun Bitki Boyu, Taze Ağırlığı ve Kuru Ağırlığının Büyüme Eğrisi Modelleri ile Araştırılması

ÖZET

Bu çalışmada dünyanın en önemli bitkilerinden biri olan sorgum bitkisi materyal olarak kullanılmıştır. Bu bitki Türkiye'nin yarı kurak iklim koşullarına sahip Konya ilinde yetiştirilmiştir. Vejetasyon döneminde 11 hafta boyunca bitki boyu, yaş ağırlığı ve kuru ağırlığı ölçülmüştür. Bitkide büyümenin şeklini belirlemek amacıyla bazı büyüme modelleri kullanılmış ve modellerin parametreleri tanımlanmaya çalışılmıştır. Brody, Gompertz, Von Bertalanffy, Logistic ve Log-Logistic modellerinin karşılaştırılmasında belirleme katsayısı (R^2), Pseudo R^2, Hata Kareler Ortalaması ve Akaike Bilgi Kriteri istatistikleri dikkate alınmıştır. Bitki boyu için uygun bulunan Gompertz modelinin R^2, Pseudo R^2, Hata Kareler Ortalaması ve Akaike Bilgi Kriteri değerleri sırasıyla 0.998, 0.999, 23.162 ve 21.013 olarak bulunmuştur. Yaş ağırlık için uygun bulunan Von Bertalanffy modelinin R^2, Pseudo R^2, Hata Kareler Ortalaması ve Akaike Bilgi Kriteri değerleri sırasıyla 0.995, 0.998, 1817.141 ve 41.993 olarak elde edilmiştir. Kuru ağırlık için uygun bulunan Log-Logistik modelinin R^2, Pseudo R^2, Hata Kareler Ortalaması ve Akaike Bilgi Kriteri değerleri sırasıyla 0.998, 0.9993, 51.007 ve 24.784 olarak

Biyometri

Araştırma Makalesi

Makale Tarihçesi
Geliş Tarihi : 07.06.2023
Kabul Tarihi : 19.10.2023

Anahtar Kelimeler
Büyüme eğrisi modelleri
Olgunlaşma indeksi
Büküm noktası
Sorgum
Bitki karakteristikleri

hesaplanmıştır. Bitki boyu, yaş ve kuru ağırlık gibi önemli bitki özelliklerinin tanımlanması, maksimum bitki boyu ve ağırlığının hesaplanması ve ortalama büyüme hızının belirlenmesi açısından doğrusal olmayan matematiksel büyüme modellerinin faydalı yöntemler olduğu önerilebilir. Sonuç olarak sorgum bitkisinde bitki boyu, bitkinin yaş ve kuru ağırlığı gibi farklı özelliklerinde büyüme eğrisi modelleri farklı sonuçlar göstermiştir.

Atıf İçin : Çelik, Ş., Gönülal, E., & Tutar, H., (2024). Sorgumun Bitki Boyu, Taze Ağırlığı ve Kuru Ağırlığının Büyüme Eğrisi Modelleri ile Araştırılması. *KSÜ Tarım ve Doğa Derg 27* (4), 994-1004. DOI: 10.18016/ksutarimdoga.vi. 1310574.

To Cite: Çelik, Ş., Gönülal, E., & Tutar, H., (2024). Investigation of Plant Height, Fresh, Weight, and Dry Weight of Sorghum with Growth Curve Models. *KSU J. Agric* Nat 27 (4), 994-1004. DOI: 10.18016/ksutarimdoga.vi. 1310574.

INTRODUCTION

Sorghum bicolor (L.) Moench is a plant belonging to the *Poaceae (Gramineae)* family. It is an essential staple food for millions in developing countries, mostly in semi-arid and arid tropical regions (Abreha et al., 2022). Provides fiber, protein-rich and gluten-free nutrition (McCann et al., 2015; Impa et al., 2019). In addition to food use, it is utilized as a raw material source for bioethanol production (Mathur et al., 2017). It is used in the livestock and biofuel industry in America and other developed countries (McLaren et al., 2003). Sorghum is a warm-season grassy C4 plant grown in different ecological conditions. It requires less fertilizer than many economically important plants and is tolerant to drought, high temperature, and salinity (Mastrorilli et al., 1999; Gnansounou et al., 2005; Tesso et al., 2005; Almodares et al., 2007). Its successful cultivation in semi-arid and arid regions makes sorghum an important component (Murungweni et al., 2016; USDA-FAS, 2018).

Sorghum is the fifth most important cereal crop in the world after rice, wheat, corn, and barley. According to FAO reports, in 2021, 40.9 million hectares of land and 61.3 million tons of production were made worldwide. In terms of production share, Africa (42.8%) ranks first, followed by America (38.5%), Asia (14.2%), Oceania (2.7%) and Europe (1.9%). In terms of production, the USA (11.3 million tons) is in the first place, followed by Nigeria (6.7 million tons), India (4.8 million tons), Ethiopia (4.4 million tons) and Mexico (4.3 million tons) (FAO, 2022).

The use of mathematical growth models to describe growth is common in the agricultural sciences (Sari et al., 2019). The growth models can be used to describe a biological process, such as seed germination (Sousa et al., 2014) and plant growth (Bem et al., 2017, 2018). In addition, nonlinear regression and growth models are still little used when statistical analysis is made in field crop trials, and when used, growth models are mostly adjusted according to accumulated production data. Nonlinear mathematical growth models have been used in some plants (Jane et al., 2020; Lacasa et al., 2021; Rahemi-Karizaki et al., 2021; Liu et al., 2021; Alam et al., 2022; Karizaki et al., 2022).

Up until the harvest point for ensiling, linear and nonlinear modeling techniques such as linear, quadratic, and Wood models were used to characterize the chemical composition and evaluate the biometric characteristics of pearl millet, corn, and sorghum. Growth models were used in the maize, pearl millet, and sorghum crops to characterize leaf growth up to the harvest point for ensiling (Chrisostomo et al., 2022). Non-linear regression analysis was applied to data on the dry weight of sorghum biomass that was gathered throughout the growing season in Italy (Pannacci and Bartolini 2016).

In this study, fresh weight, dry weight, and plant height parameters of the sorghum plant, which is one of the most important plants in the world, were measured for 11 weeks. It is aimed to model the obtained data by comparing it with 5 different growth curve methods.

MATERIAL and METHOD

The research was conducted in the province of Konya, located in the Central Anatolia Region of Türkiye, in 2020. Early Sumac variety of sorghum plant was used as material. The area where the study was carried out; is an area with a clay loam structure, not very rich in organic matter, high lime content, pH value between 7.6 - 8.3, and no salt problem (Table 1).

The plant vegetation period is May-August. When Table 2 is examined; according to the climate data of the study area for long years, the average temperature was 20.7 °C and the highest average temperature was 23.5 °C (July). According to long years, the average temperature in the sorghum growing period was 15.9 °C in May, 20.1 °C in June, 23.5 °C in July and 23.3 °C in August. Considering the precipitation data, it was seen that the average for long years was 82.4 mm. In the study year, the average temperature of the sorghum vegetation period was 21.5 °C, while the total precipitation amount was 74.3 mm.

In the study, the plots were formed in 4 rows, 5 cm on the row, 45 cm between the rows, and 5 m in length. The parcel dimensions are arranged as 1.8 m x 5 m = 9 m². In the study, sowing was done on 12 May 2020, and 50 mm of water was given to all plots. After soil preparation, phosphorus fertilizer (9 kg/da) was given and a total of 18 kg N was given throughout the period, taking into account the soil analysis with planting. All of the phosphorus fertilizer and 3 kg/da of nitrogen fertilizer were given with the planting, and the remaining part of the nitrogen fertilizer was distributed equally to the plots by drip irrigation in the form of 4 parts (15 kg/da). In weed control, both mechanical and drug control methods were applied. In the study, irrigation was done with a drip irrigation system, and a total of 480 mm of irrigation water was given.

Table 1. Some soil properties of the experimental area
Çizelge 1. Deneme alanına ait bazı toprak özellikleri

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	(structure)	Field capacity %)	Wilting point %)	Volume weight (g/cm^3)	pH	EC (dSm^{-1})	Lime %)	Organic Matter (%)	P_2O_5 (kg da^{-1})	K_2O (kg da^{-1})
0-30	9.6	29.4	61.0	CL	26.2	16.8	1.24	7.9	0.65	45.6	1.4	12.7	85
30-60	10.4	30.7	58.9	CL	27.3	17.3	1.35	8.3	0.49	35.9	1.2	11.6	63
60-90	9.1	28.4	62.5	CL	28.4	17.7	1.33	8.4	0.42	39.4	1.1	10.8	44

Table 2. Climate data of the study area (1929-2019, 2020)
Çizelge 2. Çalışma alanın iklim verileri (1929-2019, 2020)

Years		May	June	July	August	Average/Total
Long Years (1929-2019)	Avr. Tem. (°C)	15.9	20.1	23.5	23.3	20.7
	Max. Tem.(°C)	22.4	26.7	36.6	30.2	29.0
	Min. Tem.(°C)	8.6	12.6	15.9	15.6	13.2
	Precipitation (mm)	43.4	25.7	7.0	6.3	82.4
2020	Avr. Tem. (°C)	16.2	20.3	25.5	23.8	21.5
	Max. Tem.(°C)	34.5	34.4	36.2	36.3	35.4
	Min. Tem.(°C)	0.3	5.8	11.5	8.3	6.5
	Precipitation (mm)	41.7	20.1	7.5	5.0	74.3

In the study; From 22 June until 1 September, plant height, fresh weight, and dry weight measurements were made weekly for a total of 11 weeks. Data were obtained from 3 randomly selected plants each week. Brody, Gompertz, Logistic, Von Bertalanffy, and Log-Logistic non-linear functions were used in the study. Table 3 lists the formulas, growth rates, and inflection point locations for these functions. The asymptotic weight or length is referred to as the A parameter in all models, and all other parameters are described as constants relating to the shape and instant growth rates of the growth curve. B is the integration constant and k is the maturity rate (Winsor, 1932; Brody, 1945; Bertalanffy, 1957; Nelder, 1961; Brown et al., 1976; Blasco et al., 2003; Bahreini Behzadi et al., 2014; Rządkowski et al., 2015).

Table 3. Model expressions and parameters of growth functions
Çizelge 3. Büyüme fonksiyonlarının model ifadeleri ve parametreleri

Model	Equation	IPT	IPW
Brody	$Y_t = A(1 - b\exp(-kt))$	---	---
Gompertz	$Y_t = A\exp(-b\exp(-kt))$	$\ln(b)/k$	A/e
Von Bertalanffy	$Y_t = A(1 - b\exp(-kt))^3$	$(\ln 3b)/k$	8A/27
Logistic	$Y_t = A/(1 + b\exp(-kt))$	$-ln(1/b)/k$	A/2
Log-Logistic	$Y_t = A/(1 + b\exp(-kln(t)))$	$[(1+k)/b(k-1)]^{-1/k}$	A(k-1)/(2k)

Y_t: Plant length/weight, A: Asymptotic length/weight, b: Integration constant, k: Maturing index. IPT: Point of inflection time, IPW: Point of inflection weight

In model fit, both individual and average total data were analyzed. Since the analysis results of individual and averaged data were very close to each other, the analysis results of averaged data were evaluated in the study. In other words, the analysis was not made individually, but as a single analysis in the data set created by taking the average of 3 observations measured every week. These analyses were carried out as a general analysis for each feature. Analyzes were carried out with the SPSS 25.0 package program. Levenberg-Marquardt algorithm was chosen for model fitting.

To select the best model, coefficient of determination (R^2), number of iterations, Mean Square Error (MSE), and Akaike information criterion (AIC) were performed (Echeverri et al., 2013; Tariq et al., 2013; Üçkardeş et al., 2013; Lupi et al., 2015; Yavuz et al., 2019). For each of these criteria, the optimum status was the highest level of the determination coefficient (pseudo R^2), the smallest number of the iterations needed, and the lowest value of the Akaike information criterion and Mean Square Error (Thomas et al., 2009; Yavuz et al., 2019). The Akaike information criterion was calculated as:

$$AIC = n * ln\left(\frac{SSE}{n}\right) + 2k \quad (1)$$

The R^2 and pseudo R^2 was calculated following:

$$R^2 = 1 - \frac{SSE}{SST} \quad (2)$$

$$pseudo\ R^2 = 1 - \frac{SSE}{SST_C} \quad (3)$$

The formula of MSE is as follows:

$$MSE = \frac{SSE}{n-k} \quad (4)$$

Where k is the number of parameters +1, SSE is the residuals sum of squares and n is the number of observations. SST is the total sum of squares, and SST_C is the adjusted overall sum of squares.

RESULTS and DISCUSSION

The estimated parameters of the 11-week plant height measurements of the sorghum plant are presented in Table 4. All the estimated growth curve models fit well with the observed growth curves (R^2>0.99) in plant length (Table 4 and Figure 1).

Following analyses utilizing various non-linear growth functions, it was determined that the values estimated for A, which represented the mature length in each function (316.592-610.934 cm, Table 4) were reliable.

The values estimated for the k (maturing index) parameter are -0.072, 0.31, 0.234, 0.53, and 1.203 in Brody, Gompertz, Von Berttalanffy, Logistic, and Log-Logistic models, respectively (Table 4). The point of inflection time for plant length is 4.184, 3.686, 5.037, and 5.886 in Gompertz, Von Berttalanffy, Logistic, and Log-Logistic models, respectively. The point of inflection length is 128.656, 111.643, 158.296, and 266.443 in Gompertz, Von Berttalanffy, Logistic, and Log-Logistic models, respectively (Table 4). The Brody model has no inflection point.

As seen in Table 4, the model with the best fit is the Gompertz model.

Table 4. Parameter coefficients and goodness of fit criteria for growth models (plant length).
Çizelge 4. Büyüme modelleri için parametre katsayıları ve uyum kriterleri (bitki uzunluğu).

Model	Brody	**Gompertz**	Von Bertalanffy	Logistic	Log-Logistic
A	610.934	349.722	376.794	316.592	581.198
b	0.979	2.683	0.625	8.494	13.468
k	-0.072	0.31	0.234	0.53	1.203
R^2	0.993	0.998	0.998	0.995	0.996
Pseudo R^2	0.9985	0.9996	0.9995	0.9989	0.9993
MSE	87.786	23.162	26.142	63.944	39.039
AIC	27.378	21.013	21.591	25.864	23.506
IPT	---	4.184	3.686	5.037	5.886
IPW	---	128.656	111.643	158.296	266.443

Models with the best goodness of fit are represented in bold

Table 5 provides the expected parameters for the sorghum plant's fresh weight measurements at 11 weeks. All of the calculated growth curve models (R2>0.99) in plant fresh weight fit the observed growth curves quite well (Figure 3). Several non-linear development functions were used in the analyses, and the values calculated for the A parameter, which in each function denotes the mature fresh weight, were found to be 311.557-1767.663 g (Table 5).

The values estimated for the k (maturing index) parameter are -0.001, 0.385, 0.288, 0.671, and 2.592 in Brody, Gompertz, Von Berttalanffy, Logistic, and Log-Logistic models, respectively. The point of inflection time for plant fresh weight was 5.644, 5.257, 4.564, and 5.472 in Gompertz, Von Berttalanffy, Logistic, and Log-Logistic models, respectively. The point of inflection weights were 573.18, 500.233, 701.489, and 542.847 in Gompertz, Von Berttalanffy, Logistic, and Log-Logistic models, respectively (Table 5).

In the Brody model in Tables 4 and 5, the k parameter was found to be negative. This means that the weekly maturation rate of plant height and fresh weight is negative. However, in other models used, the weekly maturity rate is positive and is the expected result. Weekly maturity rates of the sorghum plant until its last developmental period are generally positive and there have been studies on this (Shi et al., 2013; Chrysostom et al., 2022).

The Gompertz, Von Berttalanffy, Logistic, and Log-Logistic models for plant fresh weight's inflection point plots are shown in Figure 4.

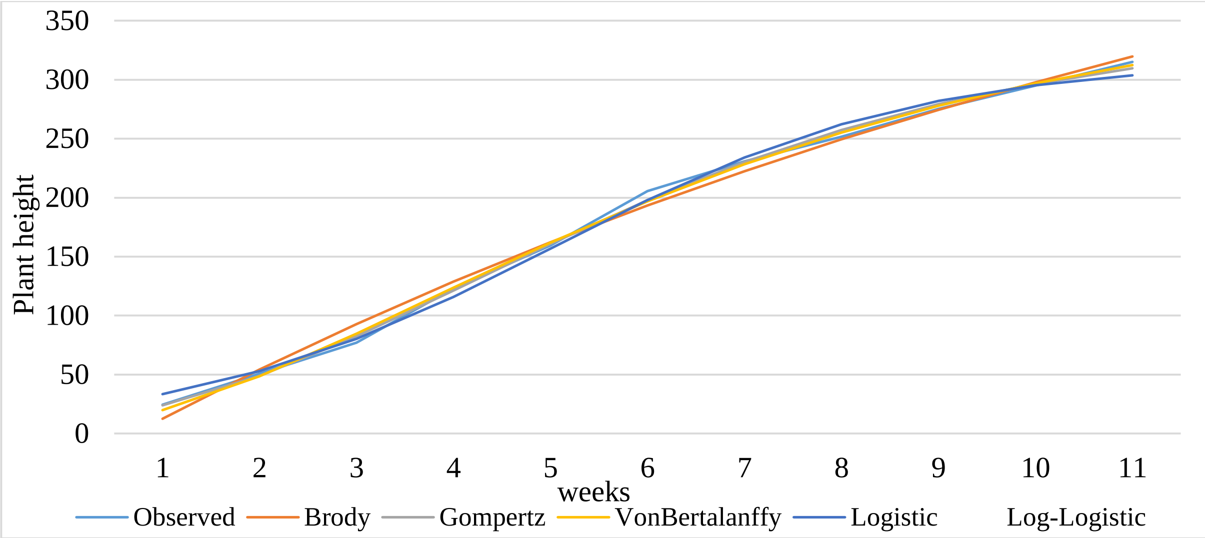

Figure 1. Growth curves of sorghum plant height (cm)
Şekil 1. Sorgum bitki boyunun büyüme eğrileri

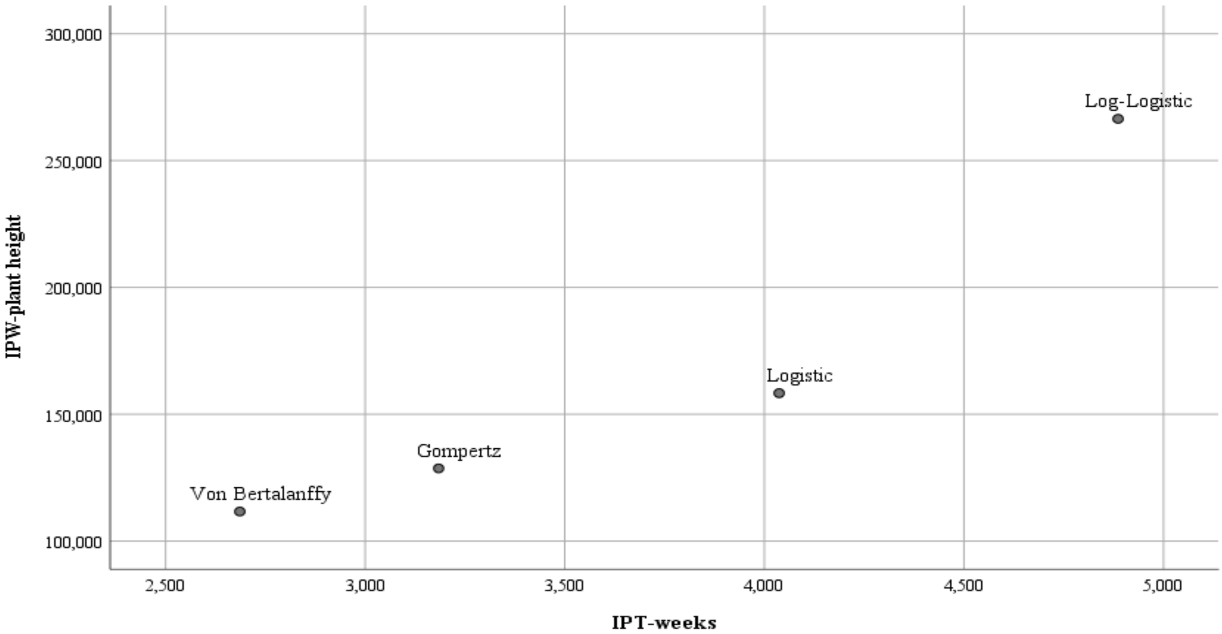

Figure 2. The point of inflection time for plant length
Şekil 2. Bitki uzunluğu için bükülme zamanı noktası grafiği

Table 5. Parameter coefficients and goodness of fit criteria for growth models (plant fresh weight).
Çizelge 5. Büyüme modelleri için parametre katsayıları ve uyum kriterleri (bitki yaş ağırlığı).

Model	Brody	Gompertz	**Von Bertalanffy**	Logistic	Log-Logistic
A	311.557	1558.06	1688.287	1402.98	1767.663
b	1	5.976	1.136	35.294	109.523
k	-0.001	0.385	0.288	0.671	2.592
R^2	0.974	0.994	0.995	0.987	0.993
Pseudo R^2	0.9903	0.9977	0.9980	0.9952	0.9979
MSE	8992.44	2197.14	1871.141	4481.04	1940.435
AIC	49.493	42.760	41.993	46.165	42.167
IPT	---	5.644	5.257	4.564	5.472
IPW	---	573.18	500.233	701.489	542.847

Models with the best goodness of fit are represented in bold

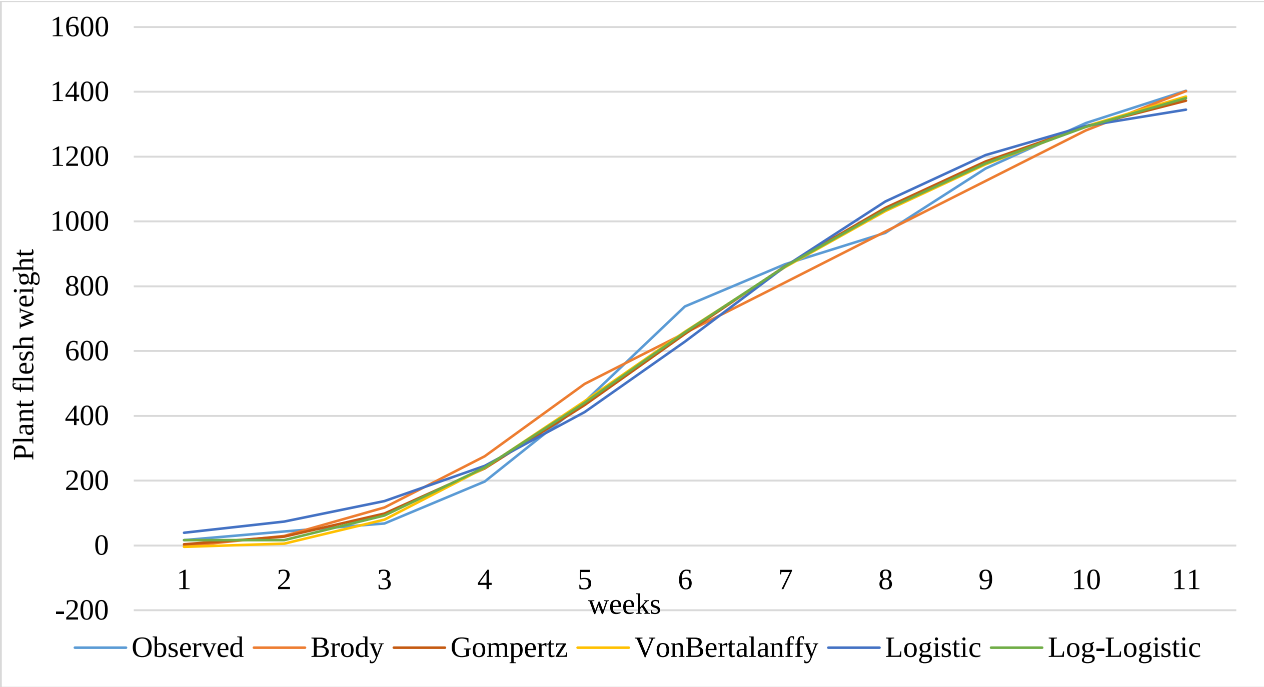

Figure 3. Growth curves of sorghum plant fresh weight
Şekil 3. Sorgum bitkisi yaş ağırlığının büyüme eğrileri

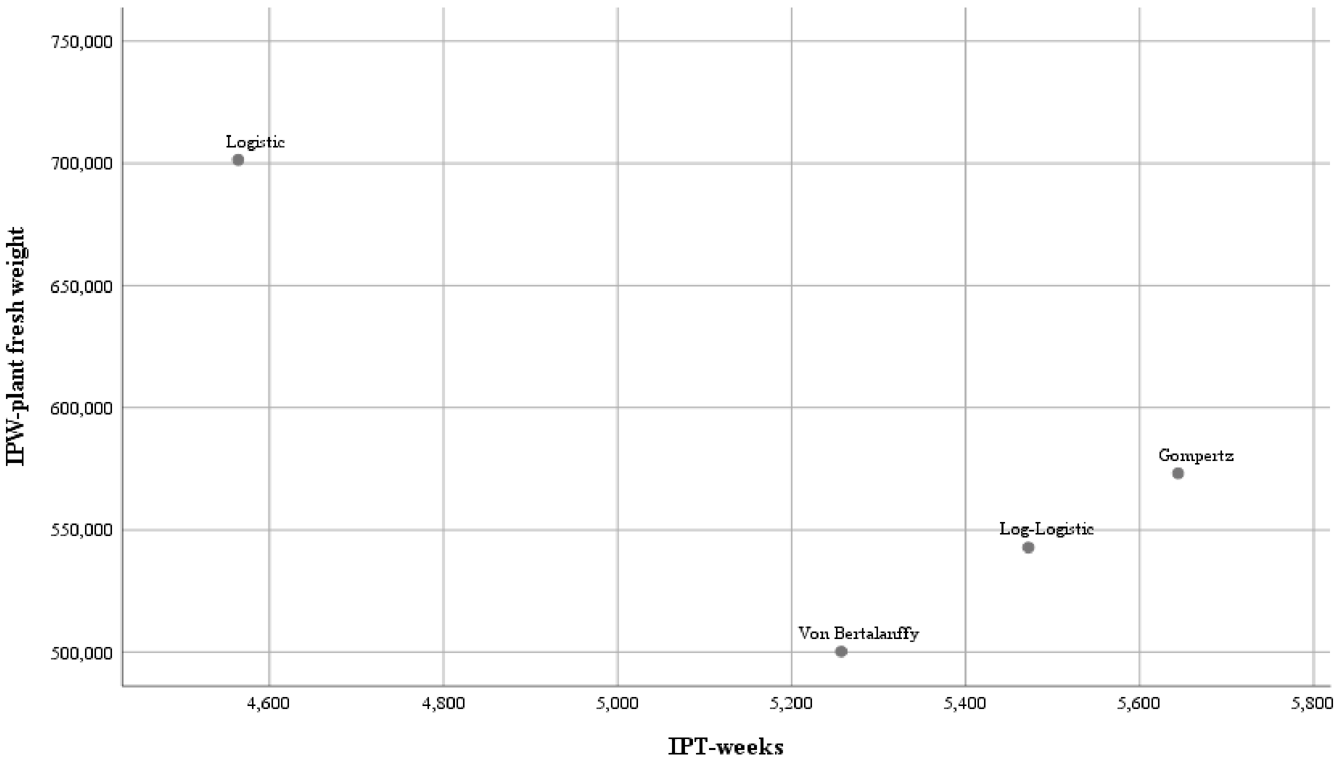

Figure 4. The point of inflection time for plant fresh weight
Şekil 4. Bitki yaş ağırlığı için bükülme zamanı noktası grafiği

Table 6 provides the expected parameters for the sorghum plant's 11-week plant dry weight measurements. In terms of plant dry weight, the estimated growth curves from models suit the observed growth curves well (R2>0.99) (Figure 5).

The analyses were carried out using several non-linear growth functions, and the values estimated for the A parameter, which represents the asymptotic dry weight in each function, were established (393.345-752.232 g, Table 6).

The values estimated for the k (maturing index) parameter are 0.001, 0.365, 0.205, 0.722, and 3.507 in Brody, Gompertz, Von Berttalanffy, Logistic, and Log-Logistic models, respectively. The point of inflection time (week) for plant fresh weight is 7.109, 7.353, 5.708, and 7.137 in Gompertz, Von Berttalanffy, Logistic, and Log-Logistic models, respectively. The point of inflection weight is 206.974, 222.884, 234.886, and 208.863 in Gompertz, Von Berttalanffy, Logistic, and Log-Logistic models, respectively (Table 6).

Table 6. Parameter coefficients and goodness of fit criteria for growth models (plant dry weight).
Çizelge 6. Büyüme modelleri için parametre katsayıları ve uyum kriterleri (bitki kuru ağırlığı).

Model	Brody	Gompertz	Von Bertalanffy	Logistic	**Log-Logistic**
A	393.345	562.613	752.232	469.771	584.35
b	1	9.299	1.226	110.847	1042.831
k	0.001	0.365	0.205	0.722	3.507
R^2	0.937	0.998	0.996	0.998	0.998
Pseudo R^2	0.9709	0.9993	0.9984	0.9992	0.9993
MSE	2202.82	53.532	124.629	55.26	51.007
AIC	42.773	25.015	29.052	25.167	24.784
IPT	---	7.109	7.353	5.708	7.137
IPW	---	206.974	222.884	234.886	208.863

Models with the best goodness of fit are represented in bold

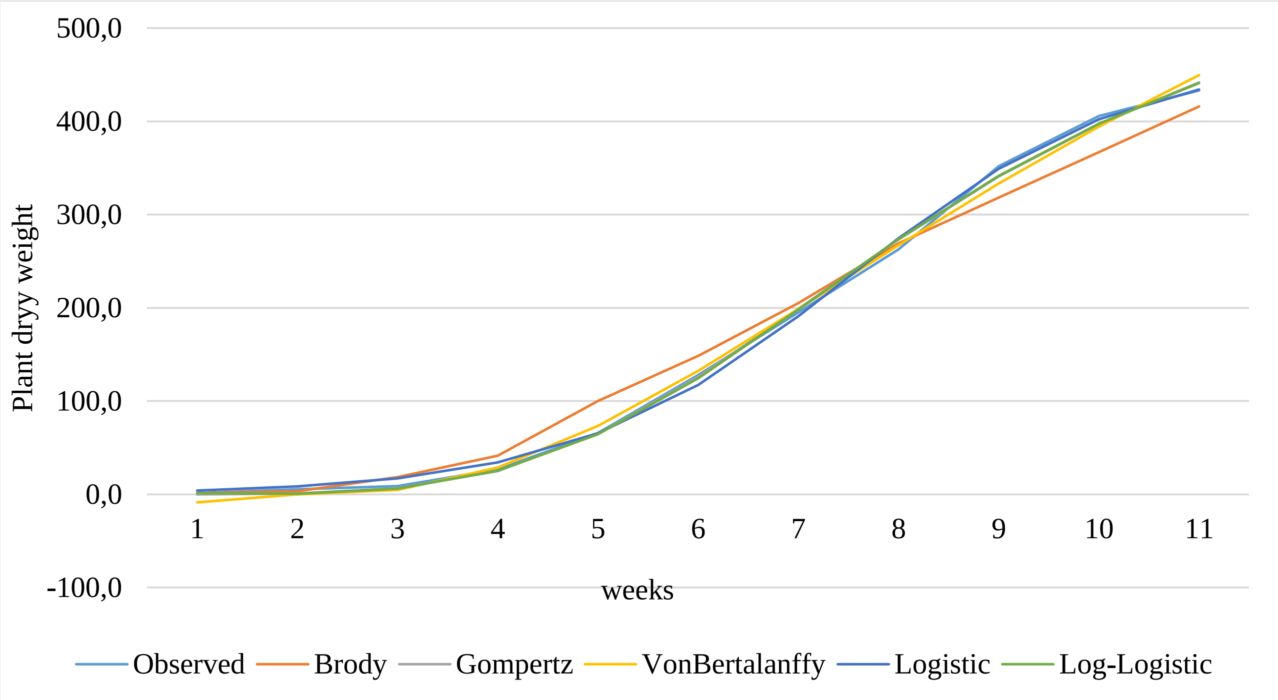

Figure 5. Growth curves of sorghum plant dry weight
Şekil 5. Sorgum bitkisi kuru ağırlığının büyüme eğrileri

Figure 6 displays the inflection point charts for the Gompertz, Von Bertalanffy, logistic, and log-logistic models for plant dry weight.

Tables 4, 5, and 6 explain the goodness of fit statistics obtained for the five models studied. It was observed that for plant length (Table 4), the Gompertz model provided the best fit. On the other hand, in what concerns fresh and dry weight, different models provided best fits for datasets of different features. Different growth curve models with different characteristics showed the best performance. It was observed that for plant fresh weight (Table 5), the Von Bertalanffy model provided the best fit. It was observed that for plant dry weight (Table 6), the Log-Logistic model provided the best fit. Thus, it was not possible to determine a model as being superior to the others.

Descriptive statistics regarding plant height, fresh weight, and dry weight are presented in Table 7.

In a study (Chrisostomo et al., 2022), while leaf diameter and length had a superior fit to the nonlinear Wood model, the biometric variables plant height and leaf width had a better fit to the linear model. Corn, pearl millet, and sorghum did not differ from one another in terms of the biometric variables (p=0.1863), and the model curves for corn and sorghum overlapped for all variables. The Gompertz model provided the best fit for leaf growth. In this study, the Gompertz model was the most appropriate model for plant height. It seems to be compatible with the results of this study in that the best model is the same.

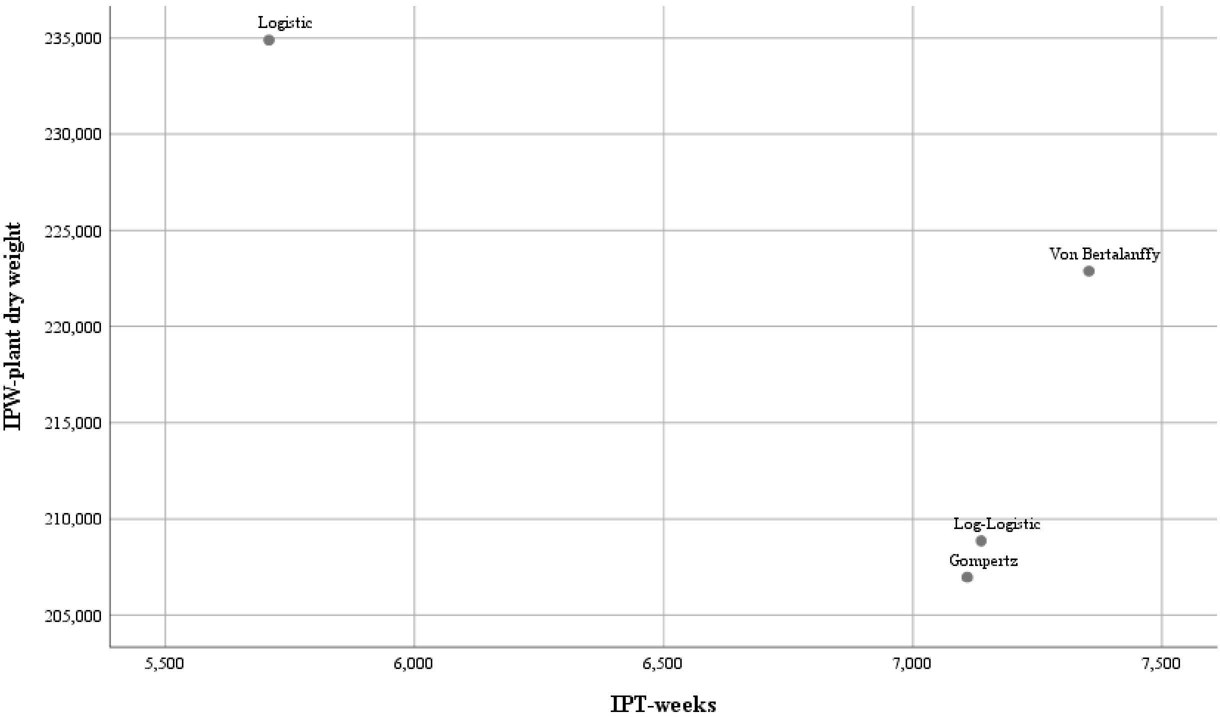

Figure 6. The point of inflection time for plant dry weight
Şekil 6. Bitki kuru ağırlığı için bükülme zamanı noktası grafiği

Table 7. Descriptive statistics of plant height (cm), plant fresh weight (g) and plant dry weight (g) ($\bar{X} \mp s_{\bar{x}}$)
Çizelge 7. Bitki boyu (cm), bitki yaş ağırlığı (g) ve kuru ağırlığına (g) ait tanımlayıcı istatistikler ($\bar{X} \mp s_{\bar{x}}$)

Weeks	N	Plant height	Plant fresh weight	Plant dry weight
1	3	24.333∓0.882	16.000∓0.577	1.470∓0.057
2	3	50.667∓3.480	43.333∓3.333	5.300∓0.401
3	3	77.000∓2.309	68.333∓4.410	8.767∓0.601
4	3	123.000∓7.211	196.667∓34.921	26.733∓4.823
5	3	159.333∓11.566	443.333∓85.942	65.767∓11.919
6	3	205.667∓14.769	736.667∓13.017	128.000∓4.359
7	3	230.667∓17.285	868.000∓20.551	195.000∓8.660
8	3	251.667∓14.814	965.000∓29.297	262.667∓3.930
9	3	275.333∓6.360	1163.333∓86.667	351.900∓26.467
10	3	295.000∓5.000	1303.333∓44.190	405.633∓12.632
11	3	315.000∓2.887	1403.333∓20.276	433.333∓10.929

$\bar{X}$: Mean, $s_{\bar{x}}$: Standard error.

The comparison between the observed values and the predicted values by the logistic model was displayed for the dry weight of sweet sorghum (Shi et al., 2013). In the logistic model, parameter values were found to be A=213 (asymptotic dry weight), b=7.73, and k=0.1237. The R^2 of the model was found to be 0.940. The parameter coefficients representing the sorghum dry weight in this study and the best-fitting model differed.

In Italy, sorghum hybrids' average plant height was 222 and 181 cm to biomass hybrids and forage hybrids in 2005, respectively. The sorghum hybrid's average plant height was measured at 338 and 284 cm for biomass hybrids and forage hybrids in 2006, respectively. The plant height of biomass hybrids was higher than forage hybrids as observed in 2005 with an average value of 338 cm (Pannacci and Bartolini 2016). Plant height values were found to be different from the values in this study.

In a study conducted in Italy, the plant height of different varieties of sorghum plants was found to be between 199 and 344 cm (Habyarimana et al., 2004).

The highest plant height was obtained from the H 132 variety with 344 cm. This was followed by Mamhonne (295 cm), IS 21055 (291 cm), and Brown sweta (291 cm). When compared to the sorghum plant height in this study, H 132 sorghum was higher than the result of this study, while other varieties were lower.

CONCLUSION

In this study, 5 different growth curves were compared using the plant height, and plant fresh and dry weights from the day of emergence to the 11th week of the sorghum plant. In the Gompertz model that best describes the plant length, the asymptotic plant length (A) was estimated as 349.7 cm and the adult growth rate (k) was 0.31. Gompertz model $Y_t = 349.7\exp(-2.683\exp(-0.31t))$ was determined as.

In the Von Berttalanffy model that best describes the plant's fresh weight; the maximum fresh plant weight (A) was estimated at 1688.287 g and the adult growth rate (k) was 0.288. The time of the highest wet weight gain was 5.257 weeks. Von Berttalanffy model $Y_t = 1688.287(1 - 1.136\exp(-0.288t))^3$ was determined as.

In the Log-Logistic model that best describes the plant dry weight, the maximum dry weight of plants (A) was estimated as 584.35 g and the adult growth rate (k) was 3.507. Log-Logistic model $Y_t = 584.35/(1 + 1042.831\exp(-3.507ln(t)))$ was determined as.

Although the growth curves appear to be close to each other when looking at the figures, it has been determined that the model fits give different results. As a result, when the 11-week growth curves of the plant were examined, plant height, and fresh and dry weight characteristics were modeled differently. Brody's model showed the lowest model performance of all models. Gompertz, Von Bertalanffy, and Log-Logistic models were the models that best describe the growth for plant height, wet weight, and dry weight in sorghum plants, respectively. Defining growth is important in determining the most appropriate time for agricultural practices. Growth differences seen between plant characteristics require the use of different models in the adaptation of growth data. In choosing the model to be used in the fitting of growth curves, the structure of the data of the estimated parameters should be considered. With such growth functions, it may be possible to predict the plant height, fresh weight, and dry weight that plants can reach in the future.

Author's Contributions

The contribution of the authors is equal.

Statement of Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

REFERENCES

Abreha, K. B., Enyew, M. A., Carlsson, S., Vetukuri, R. R., Feyissa, T., Motlhaodi, T., Ng'uni, D., & Geleta, M. (2022). Sorghum in dryland: Morphological, physiological, and molecular responses of sorghum under drought stress. *Planta, 255*. [DOI: 10.1007/s00425-022-03808-0]

Alam, T., Suryanto, P., Susyanto, N., Kurniasih, B., Basunanda, P., Putra, E. T. S., Kastono, D., Respatite, D. W., Widyawan, M. H., Nurmansyah, N., Ansari, A., & Taryono, T. (2022). Performance of 45 non-linear models for determining the critical period of weed control and acceptable yield loss in soybean agroforestry systems. *Sustainability, 14*(13), 7636. [DOI: 10.3390/su14137636]

Almodares, A., Taheri, R., & Adeli, S. (2007). Inter-relationship between growth analysis and carbohydrate contents of sweet sorghum cultivars and lines. *Journal of Environmental Biology, 28*, 527-531.

Bahreini Behzadi, M. R., Aslaminejad, A. A., Sharifi, A. R., & Simianer, H. (2014). Comparison of mathematical models for describing the growth of Baluchi Sheep. *J. Agr. Sci. Tech., 14*, 57-68.

Bem, C. M., Filho, A. C., Facco, G., Schabarum, D. E., Silveira, D. L., Simões F. M., & Uliana, D. B. (2017). Growth models for morphological traits of sunn hemp. *Seminar: Ciênc. Agrár., 38*, 2933-2944.

Bem, C. M., Filho, A. C., Chaves, G. G., Kleinpaul, J. A., Pezzini, R. V., & Lavezo, A. (2018). Gompertz and logistic models for the productive traits of Sunn hemp. *J. Agric. Sci., 10*, 225-238.

Bertalanffy, L. (1957). Quantitative laws for metabolism and growth. *The Quarterly Review of Biology, 32*, 217-231.

Blasco, A., Piles, M., & Varona, L. (2003). A Bayesian analysis of the effect of selection for growth rate on growth curves in rabbits. *Genet. Sel. Evol., 35*, 21-41.

Brody, S. (1945). Bioenergetics and growth. *Rheinhold Pub. Corp. N.Y.*

Brown, J. E., Fitzhugh Jr, H. A., & Cartwright., T. C. (1976). A Comparison of nonlinear models for describing weight-age relationship in cattle. *J. Anim. Sci., 42*, 810-818.

Chrisostomo, P. H. B., Camilo, M. G., Baffa, D. F., Process, E. F., Gloria, L. S., Fernandes, A. M., & Oliveria, T. S. (2022). Biometric evaluation and nutrients of the corn, pearl millet, and sorghum crops. *Pesqulsa Agropecuaria Brasilleira, Brasília, 57*.

Echeverri, A. M. L., Bergmann, J. A. G., Toral, F. L. B., Osorio, J. P., Carmo, A. S., Mendonça, L. F., Moustacas, V. S., & Henry, M. (2013). Use of nonlinear models for describing scrotal circumference growth in Guzerat bulls raised under grazing conditions. *Theriogenology, 79*(5), 751-759. [DOI: 10.1016/j.theriogenology.2012.11.021]

FAO. (2022). Food and Agriculture Organization of the United Nations: Home. Retrieved from http://apps.fas.usda.gov/faostat/en/#data/QCL

Faci, J. M. (1991). Efecto de la densidad de plantas sobre la producción de sorgo bajo un suministro variable de riego. *IX Jornadas Te´cnicas de Riego*, 37–45, Granada, Spain.

Gnansounou, E., Dauriat, A., & Wyman, C. E. (2005). Refining sweet sorghum to ethanol and sugar: economic trade-offs in the context of North China. *Bioresource Technology, 96*, 985-1002. [DOI: 10.1016/j.biortech.2004.06.025]

Habyarimana, E., Laureti, D., Ninno, M. D., & Lorenzoni, C. (2004). Performances of biomass sorghum [Sorghum bicolor (L.) Moench] under different water regimes in the Mediterranean region. *Industrial Crops and Products, 20*, 23–28. [DOI: 10.1016/j.indcrop.2004.03.004]

IBM Corp. (2017). IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.

Impa, S. M., Perumal, R., Bean, S. R., Sunoj, V. S. J., & Jagadish, S. V. K. (2019). Water deficit and heat stress-induced alterations in grain physico-chemical characteristics and micronutrient composition in field-grown grain sorghum. *J. Cereal Sci., 86*, 124–131. [DOI: 10.1016/j.jcs.2019.02.004]

Jane, S. A., Fernandes, F. A., Silva, E. M., Muniz, J. A., Fernandes, T. J., & Pimentel, G. V. (2020). Adjusting the growth curve of sugarcane varieties using nonlinear models. *Ciência Rural, 50*.

Karizaki, A. R., Rezvantalab, N., & Gholamalipour Alamdari, E. (2022). Quantification of grain dry matter accumulation trends in barley cultivars. *Plant Physiology Reports, 1-12*. [DOI: 10.1007/s40502-022-00647-5]

Lacasa, J., Hefley, T. J., Otegui, M. E., & Ciampitti, I. A. (2021). A practical guide to estimating the light extinction coefficient with nonlinear models—a case study on maize. *Plant Methods, 17*(1), 1-11. [DOI: 10.1186/s13007-020-00720-2]

Liu, X., Woodward, J. E., Kelly, B., Lewis, K. L., Byrd, S. A., & Chen, Y. (2021). Effects of production practices on temporal disease progress of Verticillium wilt of cotton (Gossypium hirsutum L.) in the Texas High Plains, USA. *Crop Protection, 140*, 105429. [DOI: 10.1016/j.cropro.2020.105429]

Lupi, T. M., Nogales, S., León, J. M., Barba, C., & Delgado, J. V. (2015). Characterization of commercial and biological growth curves in the Segureña sheep breed. *Animal, 9*(8), 1-8. [DOI: 10.1017/S1751731115000855]

Mastrorilli, M., Katerji, N., & Rana, G. (1999). Productivity and water use efficiency of sweet sorghum as affected by soil water deficit occurring at different vegetative growth stages. *European Journal of Agronomy, 11*(3-4), 207-215. [DOI: 10.1016/S1161-0301(99)00032-4]

Mathur, S., Umakanth, A. V., Tonapi, V. A., Sharma, R., & Sharma, M. K. (2017). Sweet sorghum as biofuel feedstock: recent advances and available resources. *Biotechnol Biofuels, 10*, 146. [DOI: 10.1186/s13068-017-0829-y]

McCann, T., Krause, D., & Sanguansri, P. (2015). Sorghum—new gluten-free ingredient and applications. *Food Aust, 67*(6), 24–26. [DOI: 10.1016/j.biortech.2004.06.025]

McLaren, J. S., Lakey, N., & Osborne, J. (2003). Sorghum as a bioresources platform for future renewable resources. Proceedings 57th Corn and Sorghum Research Conference. CD ROM. American Seed Trade Association, Alexandria, VA, USA.

Murungweni, C., Van Wijk, M. T., Smaling, E. M. A., & Giller, K. E. (2016). Climate-smart crop production in semi-arid areas through increased knowledge of varieties, environment, and management factors. *Nutrient Cycl. Agroecosyst, 105*, 183-197. [DOI: 10.1007/s10705-016-9802-0]

Nelder, J. A. (1961). The fitting of a generalization of the logistic curve. *Biometrics, 17*, 89-110. [DOI: 10.2307/2527682]

Pannacci, E., & Bartolini, S. (2016). Evaluation of sorghum hybrids for biomass production in central Italy. *Biomass and Bioenergy, 88*, 135-141. [DOI: 10.1016/j.biombioe.2016.03.014]

Rahemi-Karizaki, A., Khaliliaghdam, N., & Biabani, A. (2021). Predicting the time trend of dry matter accumulation and leaf area index of winter cereals under nitrogen limitation by non-linear models. *Plant Physiology Reports, 26*(3), 443-456. [DOI: 10.1007/s40502-021-00647-5]

Rządkowski, G., Rządkowski, W., & Wójcicki, P. (2015). On some connections between the Gompertz function and special numbers. *Journal of Nonlinear Mathematical Physics, 22*, 374–380. [DOI: 10.1080/14029251.2014.911347]

Sari, B. G., Lúcio, A. D. C., Santana, C. S., Olivoto, T., Diel, M. I., & Krysczun, D. K. (2019). Nonlinear growth models: An alternative to ANOVA in tomato trials evaluation. *European Journal of Agronomy, 104*, 21-36. [DOI: 10.1016/j.eja.2019.01.002]

Sari, B. G., Lúcio, A. D. C., Santana, C. S., & Savian, T. V. (2019). Describing tomato plant production using growth models. *Scientia Horticulturae, 246*, 146-154. [DOI: 10.1016/j.scienta.2018.11.035]

Shi, P. J., Men, X. Y., Sandhu, H. S., Chakraborty, A., Li, B. L., Ou-Yang, F., Sun, Y. C., & Ge, F. (2013). The "general" ontogenetic growth model is inapplicable to crop growth. *Ecological Modelling, 266*, 1-9. [DOI: 10.1016/j.ecolmodel.2013.06.013]

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. *Cienc. Rural., 44*, 2016-2021. [DOI: 10.1590/0103-8478cr20130118]

Tariq, M. M., Iqbal, F., Eyduran, E., Bajwa, M. A., & Huma, Z. (2013). Comparison of non-linear functions to describe the growth in the Mengali sheep breed of Balochistan. *Pakistan Journal of Zoology, 45*, 661-665. [DOI: 10.17582/journal.pjz/2013.45.3.661.665]

Tesso, T. T., Claflin, L. E., & Tuinstra, M. R. (2005). Analysis of stalk rot resistance and genetic diversity among drought-tolerant sorghum genotypes. *Crop Sci., 45*, 645-652. [DOI: 10.2135/cropsci2004.0293]

Tyagi, R. C., Singh, D., & Hooda, I. S. (1998). Effect of plant population, irrigation, and nitrogen on yield and its attributes of spring maize (Zea mays). *Indian Journal of Agronomy, 43*(4), 672–676. [DOI: 10.1007/s10681-013-0885-1]

Thomas, M. S. C., Annaz, D., Ansari, D., Serif, G., Jarrold, C., & Karmiloff-Smith, A. (2009). Using developmental trajectories to understand developmental disorders. *Journal of Speech, Language, and Hearing Research, 52*(2), 336-358. [DOI: 10.1044/1092-4388(2009/07-0203)]

USDA-FAS. (2018). World Agricultural Production. Circular Series WAP10-18 [DOI: 10.1021/jf508703f]

Üçkardeş, F., Korkmaz, M., & Ocal, P. (2013). Comparison of models and estimation of missing parameters of some mathematical models related to in situ dry matter degradation. *Journal of Animal and Plant Sciences, 23*, 999–1007. [DOI: 10.11648/j.ajae.20130103.12]

Winsor, C. P. (1932). The Gompertz curve as a growth curve. *Proc. National Academy of Science, 18*(1), 1-8. [DOI: 10.1073/pnas.18.1.1]

Yavuz, E., Önem, A. B., Kaya, F., Çanga, D., & Şahin, M. (2019). Modeling of individual growth curves in Japanese quails. *Black Sea Journal of Engineering and Science, 2*(1), 11-15. [DOI: 10.32569/bsengineering.615738]