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Research article

Growth of tomato seedlings: an approach with the logistic model as a function of the product of thermal efficiency and photosynthetically active radiation

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ABSTRACT: This study aimed to evaluate the use of the product of thermal efficiency and photosynthetically active radiation (TEP) to model the growth of tomato seedlings across different growing seasons. The work was conducted in a completely randomized design with four replicates in two seasons (summer/autumn and winter/spring). Height, diameter, the Dickson's Quality Index (DQI), and total plant mass (TPM) were measured at 15, 20, 25, 30, 35 and 40 days after sowing (DAS). The logistic model was fitted for each measured variable as a function of TEP, and the partial derivatives of the fitted function estimated the critical points. The results demonstrated that the logistic function effectively explained the nonlinear relationships of seedling growth. The fit quality parameters showed high fitted coefficients of determination and low values for the standard error of fit, residual standard deviation, and intrinsic and parametric nonlinearity. It was possible to characterize the growth process of tomato seedlings in both growth periods investigated. The logistic model fitted for the studied variables as a function of TEP becomes an accurate model capable of describing growth aspects of tomato seedlings, such as growth estimation, growth speed, and growth rate, essential parameters for decision-making in tomato cultivation.
Keywords: nonlinear, precocity, production, solar radiation, temperature

Introduction

Stress resulting from fluctuations in weather conditions poses the most significant threat to global agricultural production. In the future, these threats could be further intensified by changes caused by global warming (Hossain et al., 2018). The tomato (*Solanum lycopersicum* L.) is an essential crop across all world regions. However, its production and productivity rely on several factors, including environmental conditions, nutritional availability, pest and disease pressure, and the quality of seedlings used for transplantation (Jones, 2013).

The seedling production is a critical phase because poor quality seedlings can jeopardise the overall productive success of the crop (Zhou et al., 2019). Several factors affect the quality and health of the seedlings, in particular temperature (T) and solar radiation (SR), during the seedling production phase (De Ron et al., 2016). Thus, seedling growth and development should not be evaluated solely as a function of temperature or days after transplanting, as plants respond non-linearly to temperature and exhibit sigmoidal growth (Paine et al., 2012). In this sense, non-linear models are presented as important alternatives with functional fits to describe all plant growth and development (Diel et al., 2020b; Jane et al., 2020; Sari et al., 2018; Silva et al., 2021).

Growth models considering the T and SR influence on tomato seedling production are scarce (Zhou et al., 2019). The product of thermal efficiency and photosynthetically active radiation (TEP) has been used to model the production of cucumber, tomato, cabbage, and cotton (Jia et al., 2014; Jiheng et al., 2009; Zhou et al., 2019), presenting as an efficient parameter to predict crop growth.

Various inferences can be made on growth dynamics based on experiments with repeated measurements over time using a nonlinear model and its critical points determined by the partial derivatives of the model. These critical points with biological interpretation provide accurate information as a function of time, such as growth speed, growth rate, and growth concentration (Diel et al., 2020b; Sari et al., 2018). This study aimed to investigate the potential of using the product of thermal efficiency and photosynthetically active radiation (PAR) to model the growth of tomato seedlings grown under a protected environment in two seasons.

Materials and Methods

Place of cultivation and plant material

The study was conducted in 2020 in a greenhouse in the municipality of Santa Maria, Rio Grande do Sul state, southern Brazil, at geographical coordinates 29°42′23″ S, 53°43′15″ W, altitude 95 m. According to the Köppen climate classification, the climate of the region is of type Cfa, characterized by an average air temperature of 19.1 °C, ranging from 0 to 38 °C, and an average annual rainfall of 2,040 mm (Alvares et al., 2013).

The greenhouse where the study was conducted is located at the Universidade Federal de Santa Maria and has a polycarbonate coating. It is 3.5 m in height, 12 m in width, and 20 m in length. The curtains were adjusted daily to promote ventilation, limit temperature rise in summer, and protect against strong winds in winter, preventing the entry of cold air and rainwater.

Seedlings were grown from BRS Nagai tomato seeds sown in 128-cell polyethylene trays washed with 10 % sodium hypochlorite and containing commercial Carolina® substrate. Seeds were sown at a ratio of one seed per cell. For the summer/autumn season, sowing occurred on 27 Feb 2020, and for the winter/spring season on 26 Aug 2020. After sowing, the trays were placed on benches with sprinkler irrigation to ensure the ideal moisture for seed germination. After seed germination, the trays were placed in a floating system where the trays floated with a soluble fertilizer solution (Andriolo, 2017).

Experimental design

The treatments comprised a completely randomized design (CRD) with four replicates and an experimental unit of five plants. The treatments consisted of seedlings at different stages of development differentiated by days after sowing (DAS): T1 = 15 DAS; T2 = 20 DAS; T3 = 25 DAS; T4 = 30 DAS; T5 = 35 DAS; and T6 = 40 DAS.

Morphological variables

Assessments consisted of measurements of plant height (cm), stem diameter (cm), total seedling mass (g), and the Dickson's quality index (DQI) calculated from plant total dry mass (TDM, g), slenderness index (RAD), shoot dry mass (SDM), and root dry mass (RDM), according to Eq. (1):

$$DQI = TDM / (RAD + SDM + RDM) \quad (1)$$

Meteorological variables

In both experiments, a temperature sensor installed in the greenhouse recorded the meteorological data hourly. Global solar radiation (Q) and air temperature (T) were automatically measured hourly during both growing periods.

The photosynthetically active radiation (PAR, MJ m^{-2} h^{-1}) was estimated to be 45 % of the incident global solar radiation (Assis and Mendez, 1989).

Relative thermal effectiveness

Thermal efficiency (TE) is the ratio of plant growth for one day (d) under actual temperature conditions to plant growth for one day under ideal temperature conditions. The relationship between TE and temperature can be expressed hourly according to the following Eq. (2):

$$RTE(T) = \begin{cases} 0 & (T < T_b) \\ T - T_b / T_{ob} - T_b & (T_b < T < T_{ob}) \\ 1 & (T_{ob} < T < T_{ou}) \\ T_m - T / T_m - T_{ou} & (T_{ou} < T < T_m) \\ 0 & (T < T_m) \end{cases} \quad (2)$$

where: $RTE(T)$ is the relative TE when the average temperature is T; T_b is the lower base temperature; T_{ob} is the lower limit of the ideal temperature; T_{ou} is the upper limit of the ideal temperature; T_m is the upper base temperature. For tomato seedlings, T_b = 5 °C, T_m = 35 °C and T_{ob} = 20 °C, and T_{ou} = 25 °C were assumed (Zhou et al., 2019).

Calculation of RTE and PAR product

The combined effects of RTE and PAR on seedling growth and development can be calculated as the product of RTE and PAR (TEP). A growth model can describe above ground biomass accumulation. The model multiplied the hourly values of RTE and PAR to obtain a value called HTEP for each hour of each day during the season (Jiheng et al., 2009). The formula to calculate the HTEP is shown in Eq. (3):

$$HTEP = \begin{cases} RTE \times PAR, & PAR > 0 \\ RTE, & PAR = 0 \end{cases} \quad (3)$$

where: RTE is an estimate of the temperature unit ranging from 0 to 1; PAR is the photosynthetically active radiation (MJ m^{-2} h^{-1}).

Afterward, the HTEP values were added over 24 h to obtain daily TEP (DTEP, MJ m^{-2} d^{-1}) according to the following Eq. (4):

$$DTEP = \sum_{i=1}^{24} (HTEP) \quad (4)$$

These values were added to obtain TEP accumulated during seedling development: TEP_{i+1} = TEP_i + $DTEP_{i+1}$ + ...$DTEP_n$. Total TEP was used as the independent variable in the nonlinear logistic model.

Statistical analysis

The nonlinear biologically-based logistic model was fitted between the measured values for height, root collar diameter, total plant mass, and the Dickson's Quality Index at each assessment (15, 20, 25, 30, 35, and 40 DAS) as a function of TEP according to Eq. (5):

$$Y_i = \frac{\beta_1}{1 + e^{(\beta_2 - \beta_3 X_i)}} + \varepsilon_i \quad (5)$$

where: Y_i is the variable measured on the plant (dependent variable); X_i is the RTE and PAR product (TEP) (independent variable); β_1 is the asymptotic value and its values represent the total production of the treatments; β_2 is a parameter reflecting the distance between the initial value (observation) and the asymptote, and β_3

is the parameter associated to the growth rate, and ε_i represents the random error.

The parameter estimates were determined using the ordinary least squares method with a Gauss-Newton algorithm. Later, the coefficient of determination (R^2) and the intrinsic (c^I) and parametric (c^θ) nonlinearity were calculated by using the curve method proposed by Bates and Watts (1988). Subsequently, the values $C^I \times \sqrt{F_{(\alpha,p,n-p)}}$ and $C^\theta \times \sqrt{F_{(\alpha,p,n-p)}}$ were estimated, where $F_{(\alpha,p,n-p)}$ = F tabulated as the quantile of the F distribution, where α is 0.05, p is the number of parameters in the model and n is the number of observations. The parameters are approximately unbiased if the values are below 0.3 and 1.0, respectively. Normality, homogeneity, and independence of the residuals were tested using the Shapiro-Wilk (SW) (Shapiro and Wilk, 1965), Breusch-Pagan (BP) (Breusch and Pagan, 1979) and Durbin-Watson (DW) (Durbin and Watson, 1950) tests.

If the assumptions of the mathematical model are not met, the model is adjusted using bootstrap. This practice avoids these problems and estimates precise confidence intervals for the parameters (Diel et al., 2019; Ratkowsky, 1983; Souza et al., 2010).

The coefficient of determination (R^2), the Akaike information criterion (AIC), the standard error of adjustment (SEA), the residual standard deviation (DPR), and the root mean square error (RMSE) were calculated.

The coordinates (X and Y) of the critical points of the logistic model, known as the maximum acceleration point (MAP), inflection point (IP), maximum deceleration point (MDP), and asymptotic deceleration point (ADP), were determined by setting the following derivatives equal to zero, according to the method described in Mischan et al. (2011): inflection point (IP): $\frac{d^2y(x)}{dx^2}=0$; MAP and MDP: $\frac{d^3y(x)}{dx^3}=0$; and asymptotic deceleration point (ADP): $\frac{d^4y(x)}{dx^4}=0$.

The statistical and graphical analyses were performed with the software R (R Core Team, version 4.2.1), with the packages MASS, lmtest, car, manipulate, Metrics, ggplot2, and cowplot.

Results

Dynamics of temperature and solar radiation

Temperatures inside the greenhouse were usually kept between the lower and upper base temperatures while the seedlings grew. In the summer/autumn, maximum temperatures in the first half of Mar were above 35 °C and minimum temperatures remained above 10 °C. The average temperatures were between 16.3 and 29.4 °C (Figure 1A). In the winter/spring, maximum temperatures were close to the optimum for the tomato crop, except late Sept, when the maximum temperature reached 39.7 °C. Average temperatures were below 10 °C on several days, with a minimum of 3.4 °C in the second half of Sept (Figure 1B).

During the seedling growth phase in the summer/autumn, PAR remained mostly above 3.78 MJ m^{-2} d^{-1} (or 8.4 MJ m^{-2} d^{-1} of global radiation), which is considered the trophic limit for most crops (Figure 2A). In the winter/spring, PAR levels were very low, and from sowing to the second half of Sept, crops did not have sufficient radiation levels to produce photoassimilates (Figure 2B), which coincided with the period of higher rainfall. Lower solar radiation availability in fall and winter is common due to the seasonal variation of meteorological elements.

Quality of the fit of the logistic model

The fitted logistic model for the tomato seedling growth variables showed low intrinsic and parametric nonlinearity results, that is, below 0 and 1, respectively, confirming the good fit of the variables according to the product of RTE and PAR (Table 1). The R^2 results were high, while the SEA and DPR were low. However, the assumptions of the non-linear model were not fully met in both seasons (Table 1). The model was adjusted using bootstrap to overcome this problem.

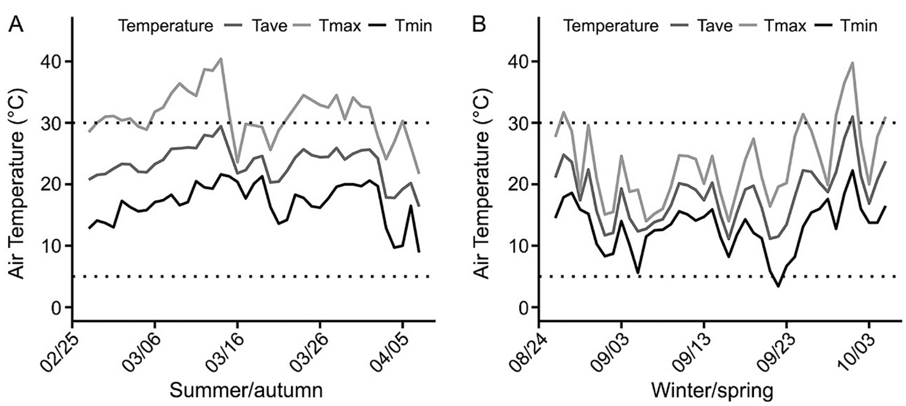

Figure 1 – A) Maximum (Tmax), minimum (Tmin) and average (Tave) air temperature during the summer/autumn season and B) the winter/spring season of tomato seedling grow in 2020. The dashed line indicates the maximum and minimum temperature tolerated by the plant.

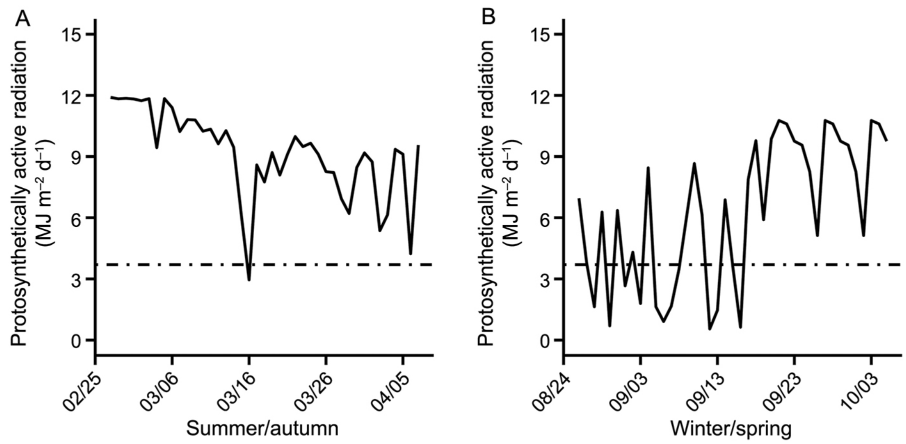

Figure 2 – A) Photosynthetically active radiation (PAR) in the protected environment during the growth of tomato seedlings in summer/autumn and B) winter/spring. The dashed line shows the trophic limit in PAR (3.78 MJ m^{-2} d^{-1}).

Growth characteristics of tomato seedlings

In the summer/autumn season, tomato seedlings had a greater height (β_1) than in the winter/spring season (58 and 36 cm, respectively) (Table 2) and grew faster, as evidenced by the parameters β_2 and β_3. These results could be related to the more significant amount of PAR available to the plants and the higher temperatures in the summer/autumn season, which allow higher plant growth (Figures 3, 4, 6 and Table 2).

Similar performance can be observed for the other variables evaluated when the summer/autumn season produced seedlings with a higher diameter, TPM, and DQI. The Dickson's quality index is an important indicator of seedling quality as it is much higher in summer/autumn due to the higher amount of PAR and temperatures closer to the optimum, allowing plants to produce photoassimilates (Figures 3, 4, 6, and Table 2).

Fitting the logistic model and the critical points of the model

The fitted logistic model for the tomato seedling growth variables as a function of the RTE and TEP (DTEP) product showed good agreement between the predicted and observed values in both seasons (Figures 5A-D and 7A-D). The RMSE values were low for all evaluated variables (Figures 5A and D).

The critical points of the model parameters can predict plant growth in both seasons. The seedlings reached the inflection point (IP) later in summer/autumn for all evaluated variables because they reached a greater height at this time. For MAP, the plants had higher values in the summer/autumn season, indicating that the growth occurred over a more extende period. In the winter/spring season, increases were less frequent; therefore the IP was reached earlier (Table 3).

Similarly, it can be observed that MDP and ADP, which indicate a decrease in seedling growth rate, started

Table 1 – The *p*-value for Shapiro-Wilk (SW) normality, Breusch-Pagan (BP) heteroscedasticity and Durbin-Watson (DW) error independence tests, estimates of intrinsic nonlinearity (c^i) and parametric (c^θ), coefficient of determination (R^2), standard error of adjustment (SEA), residual standard deviation (DPR) and Akaike's information criterion (AIC) for the fitted logistic model for tomato seedlings in two growing seasons.

Variable	SW	BP	DW	c^i	c^θ	R^2	SEA	DPR	AIC
Summer/autumn									
Height	0.93	0.02	0.01	0.08	0.83	0.97	3.02	1.75	126.00
Diameter	0.76	0.94	0.33	0.17	0.55	0.96	0.03	0.02	–99.07
DQI	0.35	0.02	0.88	0.26	0.99	0.92	0.001	0.001	–239.50
TPM	0.03	0.06	0.20	0.17	0.87	0.97	1.12	0.65	78.46
Winter/spring									
Height	0.28	0.02	0.37	0.05	0.63	0.99	1.09	0.63	77.19
Diameter	0.12	0.31	0.04	0.14	0.51	0.95	0.02	0.01	–106.10
DQI	0.85	0.02	0.96	0.15	1.00	0.97	0.0006	0.0004	–282.16
TPM	0.02	0.01	0.46	0.16	0.94	0.97	0.64	0.37	51.46

Height = plant height; Diameter = root collar diameter; DQI = Dickson's Quality Index; and TPM = total plant mass.

Table 2 – Parameter estimates (β_1, β_2, and β_3) of the models fitted for tomato seedlings in two growing seasons.

Variables	Parameter estimates		
	β_1	β_2	β_3
Summer/autumm			
Height	58.37	5.74	0.02
Diameter	0.48	6.05	0.03
DQI	0.01	8.39	0.03
TPM	18.25	8.22	0.03
Winter/spring			
Height	36.01	3.17	0.01
Diameter	0.36	3.65	0.02
DQI	0.01	5.52	0.02
TPM	10.54	7.10	0.02

β_1 = asymptotic value, representing total production; β_2 = distance between the initial observed value and the asymptotic value; and β_3 = parameter associated to growth rate. Height = plant height; Diameter = root collar diameter; DQI = Dickson's Quality Index; and TPM = total plant mass.

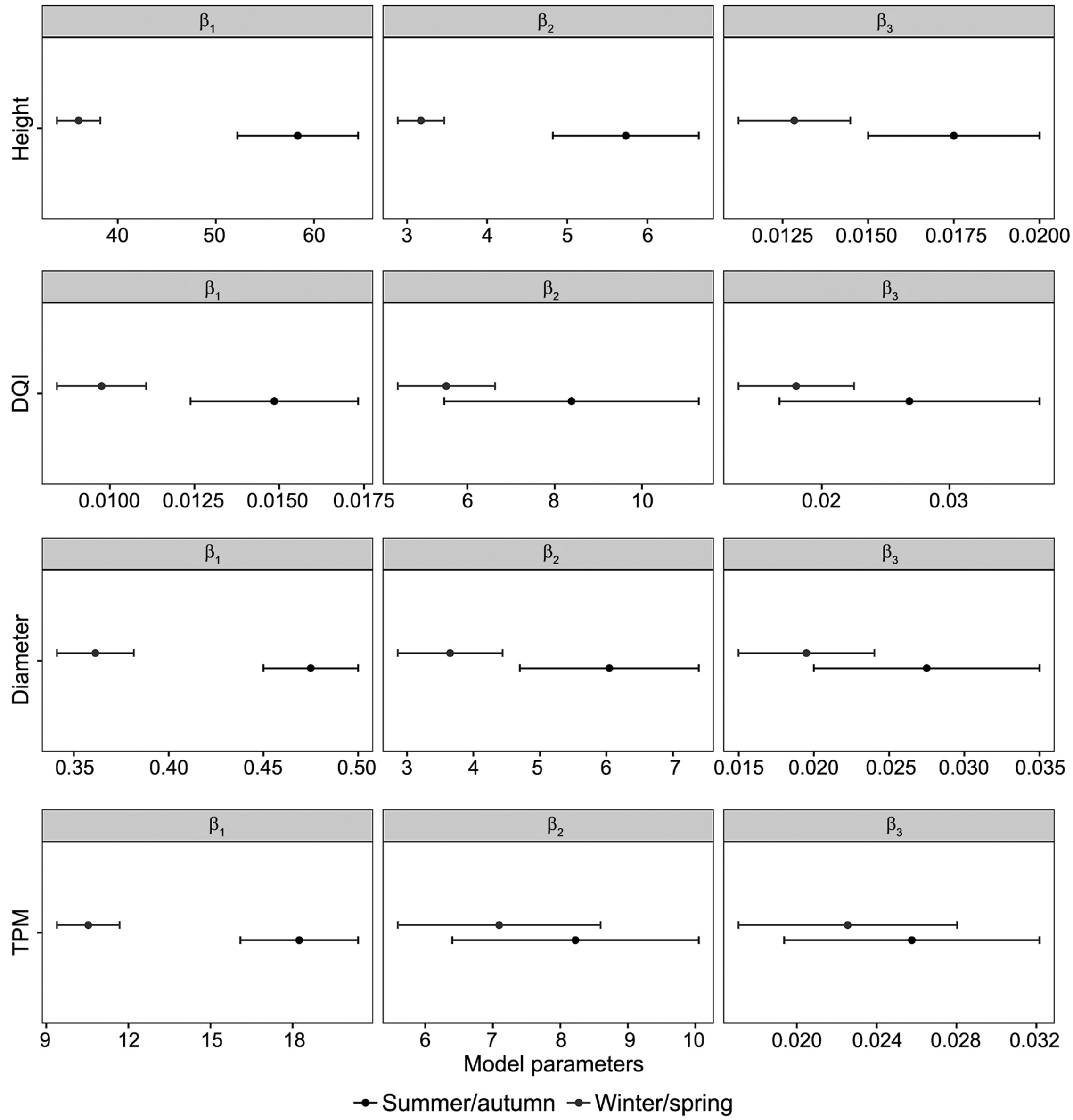

Figure 3 – Estimates of the logistic model parameters (β_1, β_2, and β_3) and corresponding bootstrap confidence intervals for the variables height, root collar diameter (Diameter), Dickson's quality index (DQI) and total plant mass (TPM) of tomato seedlings in two growing seasons.

later in the winter/spring season. This could be related to the slower growth rate caused by low temperatures during this period and low light for the plants.

Discussion

In tomato cultivation, temperatures significantly influence growth and development throughout the plant cycle (Van Ploeg and Heuvelink, 2005). In our study, temperatures were within the ideal range for the plant during the summer/autumn season, with only a few peaks above the upper base temperature. For seedling production, growth rates during the day are higher at temperatures above 20 °C (Calvert, 1964). In this study, in the winter/spring season, plants were exposed to minimum temperatures below 20 °C, even when temperatures did not exceed 5 °C. Lower temperatures decrease plant growth, as in our investigation in the winter/spring season (Kong et al., 2021). Likewise, leaf emission decreases linearly with decreasing temperature (Van Ploeg and Heuvelink, 2005).

The temperature values (air and soil) considered ideal for adequate growth and development of tomato plants vary during the different developmental stages of the plant, similar to the growth rate of the plants within

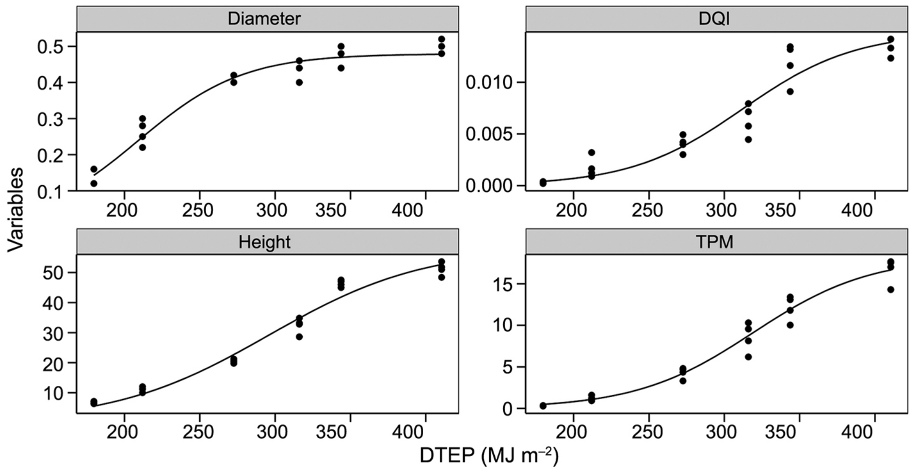

Figure 4 – Logistic model fitted to the values of root collar diameter, Dickson's quality index (DQI), plant height, and total plant mass (TPM) as a function of thermal efficiency product and photosynthetically active radiation (DTEP) for summer/autumn-grown tomato seedlings.

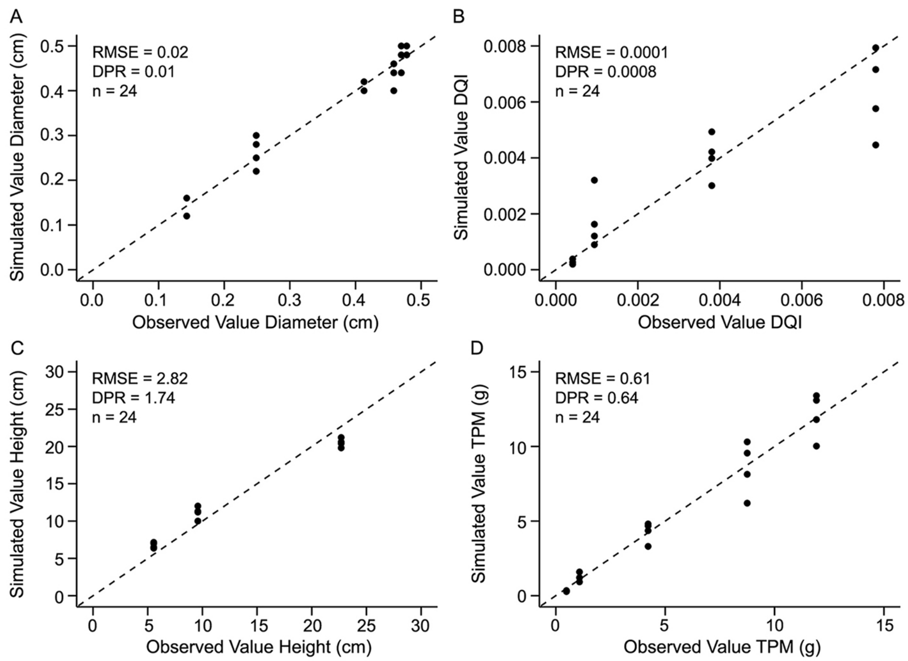

Figure 5 – A) Comparison between the simulated and observed values of root collar diameter, B) Dickson's quality index (DQI), C) plant height, and D) total plant mass (TPM) as a function of thermal efficiency product and photosynthetically active radiation for summer/autumn-grown tomato seedlings. RMSE = root mean square error; DPR = residual standard deviation; n = number of observations.

the ideal temperature range. For leaf photosynthesis, the optimal basal temperature is between 6-8 °C (Duchowski and Brazaitytë, 2001), for leaf shedding it must be above 7 °C (Adams et al., 2001), while the soil temperature must be above 8 °C for germination; however, the maximum tolerable temperature is 35 °C. For adequate plant development, air temperature must be between 12 and 30 °C. The optimum temperature range for seedling production is from 16 to 18.5 °C (Jones, 2013).

In addition, plants are highly dependent on solar radiation throughout the production cycle. Plant growth occurs when the solar radiation is above the trophic limit, which is about 8.4 MJ m^{-2} d^{-1} (FAO, 1990) or 3.78 MJ m^{-2} d^{-1} of PAR for most crops. In the present study, PAR remained above the trophic limit in the summer/autumn. In the winter/spring season, PAR was below the trophic limit at the beginning of the period, decreasing the initial plant growth.

In this study, seedling growth was modelled as a function of the product of thermal efficiency and photosynthetically active radiation precisely because temperature and PAR directly affect tomato plant growth and development (Kong et al., 2021). The results showed a good fit of the model and the intrinsic and parametric nonlinearity measures were below 1 and 0.3, respectively (Bates and Watts, 2007), suggesting that the model has a high quality of fit and exhibits properties close to linearity (Sari et al., 2018).

The logistic model parameters allowed us to draw conclusions of seedling growth in each variable. In the summer/autumn season, plants were exposed to higher temperatures and greater PAR availability than in the winter/spring. This factor increased seedling height in a shorter period in summer/autumn, plant growth in periods of high temperatures (28/29 °C), and solar radiation results in a significant elongation of the stems compared to seedlings grown at 20 °C (Gray et al., 1998).

Plants react to high temperatures in the first nine days after sowing. In addition, young plants form thicker leaves at suboptimal temperatures intercept less solar radiation and have a lower relative growth rate, which could justify the results obtained in winter/spring (Van Ploeg and Heuvelink, 2005).

Table 3 – Critical points of the logistic model adjusted for plant height (Height), root collar diameter (Diameter), Dickson's quality index (DQI), and total plant mass (TPM) in tomato seedlings in two growing seasons.

Variables	Critical points			
	IP	MAP	MDP	ADP
	Summer/autumn			
Height	295.92	227.97	363.87	414.20
Diameter	209.35	163.76	254.94	288.71
DQI	312.27	263.23	361.30	397.61
TPM	319.19	268.08	370.31	408.16
	Winter/spring			
Height	247.16	144.62	349.71	425.65
Diameter	187.16	119.61	254.71	304.74
DQI	306.79	233.58	379.99	434.21
TPM	314.67	256.27	373.08	416.34

IP = inflection point; MAP = maximum acceleration point; MDP = maximum deceleration point; ADP = asymptotic deceleration point.

The results of the logistic model confirm the influence of the product of thermal efficiency with PAR on the growth of tomato seedlings. A study conducted to develop an improved model to describe the accumulation of aboveground biomass of cotton by using the product of thermal efficiency and PAR as input variables of the model found that the product of thermal efficiency and PAR is a valuable parameter to estimate biomass accumulation in cotton (Jia et al., 2014). Another study suggested that the product of thermal efficiency and PAR could be used in simulation models to predict the quality of tomato and cabbage seedlings grown under different temperatures and solar radiation conditions (Zhou et al., 2019).

Seedling quality is a prerequisite for good performance in the field and affects crop yield (Zhou et al., 2019). In summer/autumn, the tomato seedlings in our study had a larger diameter, a higher TPM, and a higher DQI. The DQI is a crutial index developed by Dickson et al. (1960) and reflects the seedling quality. The higher the DQI, the better the quality of the seedlings. In addition, seedlings with a larger diameter and a higher TPM reflect the seedling quality. High quality seedlings are extremely important for a more successful crop establishment and, thus, for a higher harvest rate and yield (Johkan et al., 2010). Thus, improving the seedling quality by manipulating environmental conditions in nurseries is efficient; however, it is a complex and expensive process. In addition, few studies consider that combined temperature and solar radiation factors are effective for tomato seedling production (Zhou et al., 2019).

In this study, the critical points of the fitted model indicated slower growth of the evaluated variables in the seedlings during the winter/spring season, which was due to the low temperatures during this period and the low sunlight exposure for the plants (Van Ploeg and Heuvelink, 2005; Zhou et al., 2019). Critical points are analytical tools that effectively help clarify various plant

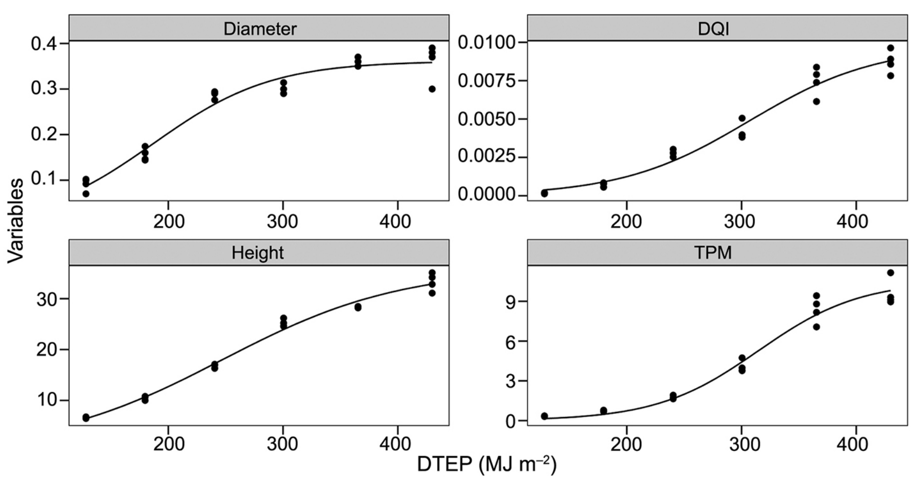

Figure 6 – Logistic model fitted to the values of root collar diameter, Dickson's quality index (DQI), height and total plant mass (TPM) as a function of thermal efficiency product and photosynthetically active radiation (DTEP) for tomato seedlings grown in winter/spring.

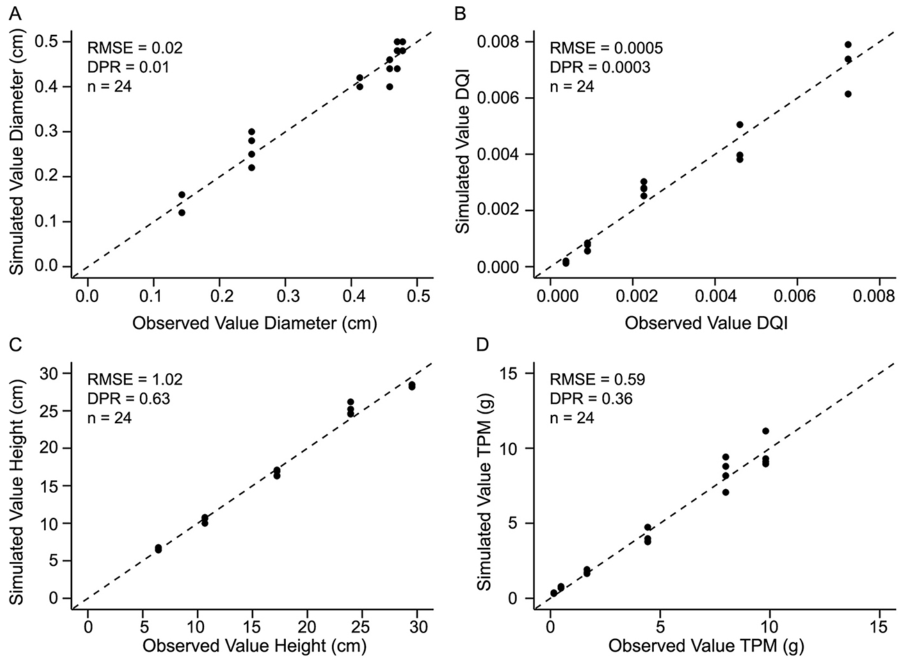

Figure 7 – A) Comparison between the simulated and observed values of root collar diameter, B) Dickson's quality index (DQI), C) height and D) total plant mass (TPM) as a function of thermal efficiency product and photosynthetically active radiation for tomato seedlings grown in winter/spring. RMSE = root mean square error; n = number of observations; DPR = residual standard deviation.

growth and development issues and greatly facilitate the decision-making process (Diel et al., 2020a, b; Sari et al., 2019a, b).

The bio-based logistic growth model for the variables height, diameter, DQI, and TPM as a function of the product of thermal efficiency and PAR is a model capable of describing aspects of tomato seedling growth in detail. The model is helpful for farmers in their decision to choose the season with the best solar radiation and temperature ranges for tomato seedling production.

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Authors' Contributions

Conceptualization: Diel MI, Lambrecht DM, Zemolin JA, Marques LE. **Data curation:** Diel MI, Tischler AL, Lambrecht DM, Zemolin JA, Marques LE. **Formal analysis:** Diel MI. **Investigation:** Diel MI, Tischler AL. **Methodology:** Diel MI, Lúcio AD, Tischler AL. **Project administration:** Diel MI, Lúcio AD. **Resources:** Diel MI. **Software:** Diel MI. **Writing - original draft:** Diel MI, Tartaglia FL, Sgarbossa J. **Writing - review & editing:** Lúcio AD, Tartaglia FL, Sgarbossa J.

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