Mathematical and computational modeling of tomato growth for 3D printing

Modelagem matemática e computacional do crescimento de tomate para impressão 3D

Modelado matemático y computacional del crecimiento del tomate para impresión 3D

Maiara Andressa Streda1
Manuel Osório Binelo2
José Antonio Gonzalez da Silva3
Marcia de Fatima Brondani Binelo4

Abstract
The physical appearance of food has a significant impact on its consumption and economic value. Research indicates consumer dissatisfaction with the quality of the tomatoes found in commerce. Physical appearance is the main characteristic that causes dissatisfaction among consumers looking for unblemished fruits. In view of this, this work aims to create a parametric model for the 3D printing of tomato fruit development that helps the producer identify the development phases of their production and compare the morphological characteristics of the fruits. For this purpose, daily experimental data on fruit growth were extracted, in addition to photographic records. In this study, a model was developed that describes the growth of fruits of the hybrid saladette tomato SM-16. This model simulates the daily growth behavior of these fruits. The mathematical and computational modeling was developed using the Python programming language and two other free software, Octave and

1Master in Mathematical Modeling. Universidade Regional do Noroeste do Estado do Rio Grande do Sul (UNIJUI). Ijuí, RS, Brasil. E-mail: maiara.streda@unijui.edu.br
2Doctor in Teleinformatics Engineering. Universidade Regional do Noroeste do Estado do Rio Grande do Sul (UNIJUI). Ijuí, RS, Brasil. E-mail: manuel.binelo@unijui.edu.br Orcid: https://orcid.org/0000-0001-7639-7663
3Doctor in Agronomy. Universidade Regional do Noroeste do Estado do Rio Grande do Sul (UNIJUI). Ijuí, RS, Brasil. E-mail: jagsfaem@yahoo.com.br Orcid: https://orcid.org/0000-0002-9335-2421
4Doctor in Mathematical Modeling. Universidade Regional do Noroeste do Estado do Rio Grande do Sul (UNIJUI). Ijuí, RS, Brasil. E-mail: marcia.brondani@unijui.edu.br Orcid: https://orcid.org/0000-0001-7505-997X
Inkscape. The growth of the tomato is represented by a logistic model, while the shape of the fruits during growth is a model developed in Artificial Neural Network. The models used, adjusted to the parameters found, proved to be adequate to describe the growth behavior of the tomato fruits of the variety studied over time.

**Keywords:** Tomato. Mathematical and Computational Modeling. Growth. Logistic Model.

**Resumo**
A aparência física dos alimentos tem um impacto significativo no seu consumo e valor econômico. Pesquisas indicam insatisfação dos consumidores com a qualidade dos tomates encontrados no comércio. A aparência física é a principal característica que causa insatisfação entre os consumidores que buscam frutas imaculadas. Diante disso, este trabalho tem como objetivo criar um modelo paramétrico para impressão 3D do desenvolvimento de frutos de tomate que auxilie o produtor a identificar as fases de desenvolvimento de sua produção e comparar as características morfológicas dos frutos. Para tanto, foram extraídos dados experimentais diários sobre o crescimento dos frutos, além de registros fotográficos. Neste estudo foi desenvolvido um modelo que descreve o crescimento de frutos do híbrido tomate salada SM-16. Este modelo simula o comportamento diário de crescimento desses frutos. A modelagem matemática e computacional foi desenvolvida utilizando a linguagem de programação Python e outros dois softwares livres, Octave e Inkscape. O crescimento do tomate é representado por um modelo logístico, enquanto o formato dos frutos durante o crescimento é um modelo desenvolvido em Rede Neural Artificial. Os modelos utilizados, ajustados aos parâmetros encontrados, mostraram-se adequados para descrever o comportamento de crescimento dos frutos de tomate da variedade estudada ao longo do tempo.


**Resumen**
La apariencia física de los alimentos tiene un impacto significativo en su consumo y valor económico. Las investigaciones indican la insatisfacción de los consumidores con la calidad de los tomates que se encuentran en el comercio. La apariencia física es la principal característica que genera insatisfacción entre los consumidores que buscan frutas sin defectos. Ante esto, este trabajo tiene como objetivo crear un modelo paramétrico para la impresión 3D del desarrollo del fruto de tomate que ayude al productor a identificar las fases de desarrollo
de su producción y comparar las características morfológicas de los frutos. Para ello se extrajeron datos experimentales diarios sobre el crecimiento del fruto, además de registros fotográficos. En este estudio se desarrolló un modelo que describe el crecimiento de frutos del tomate ensalada híbrido SM-16. Este modelo simula el comportamiento de crecimiento diario de estos frutos. El modelado matemático y computacional se desarrolló utilizando el lenguaje de programación Python y otros dos software libres, Octave e Inkscape. El crecimiento del tomate está representado por un modelo logístico, mientras que la forma de los frutos durante el crecimiento es un modelo desarrollado en Artificial Neural Network. Los modelos utilizados, ajustados a los parámetros encontrados, resultaron adecuados para describir el comportamiento de crecimiento de los frutos de tomate de la variedad estudiada a lo largo del tiempo.

**Palabras clave:** Tomate. Modelado Matemático y Computacional. Crecimiento. Modelo Logístico.

**Introduction**

In global nutrition, the tomato (Lycopersicon esculentum Mill) is one of the most popular and widely consumed crops. Its commercial value is defined by the identity and quality characteristics present in the fruit. When displayed at fruit stands, foods need to catch the consumer's eye so that they want to consume it. When it comes to tomatoes, the fruits need to be visibly healthy, with smooth skin and no blemishes, indicating quality. The size of the fruits also influences the purchase choice, as a normally sized fruit indicates it had a healthy development (FOOLAD, 2007).

The demand for tomatoes has significantly increased in recent years, and one reason for this is the awareness of healthier eating. In the year 2022, tomato production in Brazil exceeded 3.67 million tons, produced in an area close to 52 thousand hectares (IBGE, 2023). It is a known fact that increasing production can risk reducing quality, hence it is important to adopt strategies aimed at maintaining product quality, as various studies over time have pointed out consumer dissatisfaction with tomatoes for raw consumption.

In their research, Andreuccetti et al. (2003) indicate consumer dissatisfaction with the table tomatoes found in supermarkets, and their demands regarding quality. According to them, a large part of consumers look for tomatoes with the intent of consuming them raw, in
salads and side dishes, and this makes the physical appearance of the fruits the deciding factor in whether to purchase the product or not. The main characteristics that cause consumer dissatisfaction are the presence of injuries (stains, cuts, or bruises) on the external appearance, non-uniform fruits, and low availability of organic fruits. According to Ferreira, Freitas, and Lazzari (2004), the quality criteria that determine the consumer's purchase of tomatoes are firstly appearance and then aspects of texture and flavor. It is known that the producer is compensated only if their product, in this case, the tomato, is in adequate condition to go to the consumers' tables or to be processed in the industry.

Analyzing the morphological aspects of the fruit, such as size and shape, at its different stages of development, is fundamental to achieving production excellence and meeting market expectations. The ability for producers to compare the tomato at any stage of development with three-dimensional models, preferably physical ones, is a useful tool for analyzing fruit quality, as it allows for the early identification of potential diseases or any other flaws they may have. From this perspective, studies that analyze the daily growth of the fruits are relevant, as they can influence the final quality of the product, benefiting both the consumer and the producer.

Although the generation of digital images can assist the producer, the creation of concrete three-dimensional models using 3D printers allows for a superior perception of the fruit's morphological characteristics. The objective of this work is to model mathematically and computationally the growth of tomato fruits in order to develop a parametric model, for 3D printing, of the fruit's development.

Material and Methods

2.1 Experimental Procedure

At the beginning of this work, in 2020, the collection of experimental data related to the growth of tomato fruits was planned to be conducted at the facilities of the Regional Institute for Rural Development (IRDeR) belonging to the Department of Agrarian Studies at UNIJUÍ. However, due to the coronavirus pandemic and the increase in infected cases in the region, it was decided to conduct the experiment in the countryside of Porto Lucena (RS) on a rural property located geographically at 27° 50' 32" South latitude and 54° 54' 09" West longitude, at an average altitude of about 117 meters above sea level. According to the Köppen...
climate classification, is humid subtropical, characterized by hot summers and cold, humid winters.

2.1.1 Figure 1 - Satellite image of the location

Figure 1
Satellite image of the location

Source: Adapted from Google Maps.

After the location was determined, to proceed with the study, it was necessary to construct a greenhouse to house the plants of the experiment. The model adopted for this experiment was the arched roof. The structure was built of wood and entirely covered with 50% black shade cloth. To prevent possible rain from damaging the beds and plants, Clear Plastic was used at the edge of the roof, about 2 meters wide. The base of the greenhouse was built in a rectangular shape measuring 6.20m x 3.5m and 2m high at the central point.

Following the construction of the greenhouse, the soil was prepared for the transplantation of the seedlings. The experiment was conducted in an open bed, located in the central part of the greenhouse, measuring 6 m x 0.9 m. A total of 30 seedlings were transplanted when they were about 40 days old and around 20 cm in height, on September 17, 2020. Shortly after transplantation, one of the plants died, leaving 29. The spacing used was 0.7 m between rows and 0.5 m between plants.

Daily watering and pest and disease control were conducted according to recommendations for the crop, using natural fungicides and insecticides weekly, prioritizing organic cultivation. Throughout the crop cycle, weeds were controlled by manual weeding whenever necessary, and sucker removal was done when shoots were about 4 cm long, and when older branches turned yellow.

The commercial hybrid Saladette SM-16 with determinate growth was used in the experiment. Saladette cultivars, also known as Italian tomatoes, are characterized by their
Mathematical and computational modeling of tomato growth for 3D printing elongated fruits with reduced transverse diameter, are bilocular with thick pulp, intense red color, being very firm and flavorful (Machado; Alvarenga; Florentino, 2007; Gouveia, 2016). It is one of the favorites for raw consumption, as it stands out for the striking flavor of the sugar and acid ratio that correlates with a mild taste. It is also widely used for processing purposes, as it provides higher yields during processing due to the amount of pulp and its diameter, and also for having higher protein and sugar content (Monteiro et al., 2008).

The SM-16 hybrid stands out for its vigorous plants with determinate growth, high productivity and resistance, with excellent fruit set. The fruits of this variety are elongated and pear-shaped, very firm, making them ideal for the fresh market (Agranda Seeds, 2021).

Twelve random plants were selected to be monitored daily during the experiment. A mirror image of the plant layout in the greenhouse can be seen in Figure 2, with the numbers highlighted in red representing the selected plants. Although chosen randomly, care was taken to have plants from both ends and also from the central part of the bed.

**Figure 2**

*Layout of the plants in the greenhouse*

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After the onset of flowering, which was marked in the second half of October 2020, three flowers from each plant were randomly chosen. About forty days after the start of monitoring the first flowers, three more flowers from each plant were chosen, totaling six flowers per plant and 72 flowers in total for the experiment. It is notable that during this interval, other flowers were selected, however, due to the climatic conditions during the period, these flowers ended up aborting and did not produce fruit, and were not counted.

At the end of the experiment, a total of 25 fruit samples were monitored from the flower to ripening. This loss was the result of problems caused by the climatic conditions.
faced during the period which affected the plants' resilience. Days of intense heat caused some plants to wilt and also led to fruit drop, desiccation (abortion) of flowers, and apical rot.

After the flowers were chosen, they received identification tags with the plant number (P) and the fruit number (F), an example of which can be seen in Figure 3. Daily, the development of the flowers and fruits was recorded through photographs. The photographic record aided the process of determining the initial day and the final day of fruit growth, as by comparing the images, one can precisely observe the day the flower closed, which technically marks the fertilization of the ovule and the beginning of fruit formation. And in the case of the final day, marked by the change in color of the fruits, they began to show more roseate tones.

**Figure 3**

*Flowers identification*

In addition to daily photographs, the daily growth of each fruit was recorded using a caliper with a 0.02 mm scale. Every day, approximately at the same time, the length and the greatest diameter of each fruit were measured. It is important to note that the process of measuring the fruits occurred only when they were of considerable size (more than 12 mm in height and 10 mm in diameter). Before this, the fruit remained too deep within the sepals, making the process difficult. The growth of the fruits was defined as height and greater diameter, measured in millimeters. The height of the fruits was measured from the base of the petiole to the apex. Conversely, the width of the fruits was measured considering the greater diameter. Figure 4 shows examples for one of the fruits.
2.2 Computational and Mathematical Modelling

The calculations to estimate the parameters of the adopted logistic model and the growth trajectories of the fruits were carried out using packages and libraries in Python programming language version 3.8, Inkscape program version 1.0.1, and GNU Octave version 6.1.0. The main Python libraries used were SciPy, NumPy, Matplotlib, Keras, and TensorFlow.

The first step after completing the data extraction and photographic record stage was to select five images of each fruit, considering the first image of the day when the measurement process began using the caliper, and the last photo of the day when the fruit changed color indicating its ripening. The other images were selected considering an equal interval of days between them. With the selected images, the edges of the fruits were traced one by one. In Figure 5, an example of the procedure for one of the fruits can be observed. To create these edges, the bézier pen tool was used, which draws light B-spline lines and curves, available in the Inkscape software.
The SGV files were imported into a Python script, which read the B-spline edges using some main libraries. To minimize the complexity of the model, it was assumed that the tomatoes are axisymmetric. Thus, the program determined that 201 points should be created along the curve trajectory to capture the complexity of the tomato's geometry. These points were output as three vectors, one corresponding to the radius, another to the height, and the third to the trajectory distance values (L), both of dimension 1x201. Additionally, an .stl file was generated for 3D visualization. Observing Figure 5 can better understand the dynamics.

The L values are distributed along the curve trajectory in red and represent the distance located between the initial point (L1) and the end of the curve (L201), where L1 = 0 and L201 = 1. Each point of L is associated with a value from the radius vector and a value from the height vector. Parallel to this, a script was created in the Octave software, which received in the form of a 6-column matrix the data corresponding to the plant, fruit, day, normalized day, diameter, and height. The number of rows in these matrices was determined by the number of growth days for each fruit it corresponded to. From this script, it was possible to estimate the parameters of the logistic model that represents the growth of the fruits, in addition to plotting the curves and curve-fitting graphs.

Two neural networks were also developed in Python, mainly employing the Keras library, one for the heights and another for the radii. The structure of these ANNs includes a data input, a hidden layer with one neuron, and 201 outputs. The ANNs were trained using the average growth values of 25 fruits, and the logistic model parameters calculated by the previously mentioned Octave script.

Despite being of the same variety, the tomato fruits monitored in this experiment showed divergences in size and shape among themselves, and different growth behaviors. Given this, when training the ANNs with these data, they sought to minimize the input errors.
by calculating the average growth values, as well as the averages for the final diameter and height. From these data combined with the parameters of the logistic model, the ANN generated a standard fruit shape for any time t. To validate this model, a new script was developed in Octave, in which the values obtained through the artificial neural network were compared with the values extracted in the experiment. The results can be reviewed in the next chapter of this work.

Understanding nature and its phenomena is a science that has been part of human life since the earliest records. In the words of Biembengut and Hein (2003): "modeling is as old as mathematics itself, arising from applications in the daily routines of ancient peoples" (p. 08). Mathematical modeling consists of interpreting reality and seeking to understand the dynamics and behavior of phenomena, transforming real-world problems into mathematical problems and solving them. Modeling is fundamental to discovering the organizational principles and dynamic behavior of systems across various areas of knowledge, such as Physics, Chemistry, Biology, Astrophysics, Computer Science, among others (BASSANEZI, 2002).

To solve or interpret a phenomenon, it is necessary to look for modeling strategies, among the many that exist, the logistic growth model stands out here. The logistic function was developed in the 19th century to describe the growth of populations when Pierre-François Verhulst introduced his contribution with his article titled "mathematical investigations of the law of population growth," which aimed to predict the demographic evolution of a society and answer the question about the maximum sustainable population size with these limited resources (CRAMER, 2003; PASTIJN, 2006). Since then, scholars have sought to refine this model which initially was a differential equation.

However, it is known that an exponential growth model is not appropriate to describe the evolution of a population over a long period of time, even though it closely approximates the curve of the phenomenon at the start of the process, over time the growth rate tends to decrease as it approaches the saturation level. An advantage of logistic regression is that it allows the evaluation of multiple explanatory variables by extending the basic principles (PASTIJN, 2006).

Logistic growth produces an 'S'-shaped curve, also treated as sigmoid behavior. The logistic function is a nonlinear function and one of the most well-known and cited in the literature. This function is depicted with many different parameterizations, the most popular being presented by Pinheiro and Bates (2000) by the following expression:
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\[ y(x) = \frac{\phi_1}{1 + \exp((\phi_2-x)/\phi_3)} \quad (1) \]

The logistic model relates an output \( y \) to an input \( x \) through a sigmoid function or in the form of a flattened S. The logistic model presented in equations 2 and 3 was adjusted to the growth variables obtained in the experiment, height and diameter of the fruits:

\[ f(t) = d \frac{c_1}{1 + c_2 \exp(-c_3(t/T)-c_4)} + c_5 \quad (2) \]

\[ f(t) = a \frac{c_1}{1 + c_2 \exp(-c_3(t/T)-c_4)} + c_5 \quad (3) \]

where:

- \( c_1, c_2, c_3, c_4, c_5 \) are model parameters obtained by curve fitting;
- \( d \) is the average diameter of a ripe tomato;
- \( a \) is the average height of a ripe tomato; and
- \( T \) is the average time for a tomato to ripen.

The model that generates the geometry of the fruits is a parametric model; it has a parameter that is the normalized time \( t \) of the fruit’s development, in which the value 0 (zero) marks the beginning of development and 1 is the end, the fruit’s harvest point. This model generates a STL file for printing, which is based on a generalized cylinder formed by the revolution of a spline. This spline is made up of 201 coordinate points \((r, a)\) along the trajectory of the contour profile of the tomato fruit, which is considered axisymmetric. To obtain these points, two ANNs are activated, one for the vector of normalized radii and one for the vector of normalized heights (where the largest radius and the highest point in the vector are 1).

After obtaining the normalized heights and radii, they are multiplied by the values of \( a \) and \( d/2 \), respectively, which are the height and radius of the fruit obtained by a logistic growth model of the fruit. Figure 6 shows the diagram of this model.
Figure 6
Computational model diagram

Where:

• $t_n$ = normalized development time;
• $f_d(t_n)$ = diameter growth function;
• $f_a(t_n)$ = height growth function;
• $N_r(t_n)$ = ANN for the vector of radii along the curve (normalized);
• $N_a(t_n)$ = ANN for the vector of normalized heights of the curve;
• $d$ = diameter of the fruit;
• $(r_{n})' = t$ vector of normalized radii of the curve;
• $a$ = height of the fruit;
• $(a_{n})' = t$ vector of normalized heights;
• $(r)' = t$ vector of radii of the curve;
• $(a)' = t$ vector of heights of the curve;
• $C((r)' , (a)') = t$ Curve spline;
• $S(c) = t$ Surface of the tomato (generalized cylinder);
• STL = 3D file for printing.

In summary, the diagram seeks to demonstrate the stages of the developed model. The input $t_n$ of the model is the time in days of the fruit's development, given by a normalized...
value, and the output is a STL file for 3D visualization and, if desired, can be printed as a prototype.

**Results and Discussion**

As observed during the experimental period, the growth of tomato fruits from the SM-16 hybrid occurred rapidly at the beginning of this process, which could be considered exponential growth. However, over the days, this daily growth rate decreased until it stabilized at the fruit's maturation, thus establishing a logistic growth model.

The fruit growth process extended for about 40 days, meaning the fruits took an average of 40 days to ripen, counting from the day the ovule was fertilized (flower closure) to the day there was a change in color. The average diameter of the ripe fruits was 54.58 mm, ranging between 74.20 mm and 39.88 mm. The average height was 66.83 mm, with the tallest recorded height being 83.96 mm and the shortest being 50.74 mm. According to current legislation and Normative Instruction No. 33/18 of MAPA (Brazil, 2018), this result confirms the oblong type, as the longitudinal diameter is greater than the transverse.

The growth curves of the diameter and height of the 25 fruits monitored in this experiment can be seen in the following figures. Figure 7 represents the growth curves related to the height and diameter of the fruits.

**Figure 7**

_Fruit growth experimental data_

![](image)

It is evident that there is a stabilization in the size of the fruits as they approach their maximum size. It can also be noted that the tomatoes show a growth trend up to about 33 days,
 Mathematical and computational modeling of tomato growth for 3D printing

after which there is a period of smaller increments in their length and width, thus indicating a logistic sigmoid behavior trend.

With the normalized values of the fruit measurements, the parameters for fitting the logistic model were estimated using the least squares method, confirming the hypothesis of having a sigmoid behavior model. In Table 1, the values found for each of the model parameters, for both diameter and height, can be observed. In equations 4 and 5, the values are substituted into the model parameters.

Table 1
Parameter obtained for the growth model

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<td>Diameter</td>
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<td>0.6077</td>
<td>-0.307711</td>
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<tr>
<td>Height</td>
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<td>0.032351</td>
<td>4.997686</td>
<td>0.866944</td>
<td>-0.324695</td>
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c₁,c₂,c₃,c₄,c₅ = model parameters.

\[
f(t) = d \frac{1.3413}{1 + 0.1332 \exp[4.9769 \left( \frac{t}{T} \right) - 0.6077]} - 0.307711 \quad (4)
\]

\[
f(t) = a \frac{1.354796}{1 + 0.032351 \exp[4.997686 \left( \frac{t}{T} \right) - 0.866944]} - 0.324695 \quad (5)
\]

In the graphs of Figure 8, you can observe the adjusted curves of the model for both diameter and height. It is noted that the curve overlaps with the points and is within the range delimited by them, indicating a good fit. Additionally, the coefficient of correlation (R²) in the radius curve was 0.97088 and in the height curve 0.97054.
Figure 8

Model and experimental data comparison

From the .stl files generated for 3D visualization of the fruits, three sequential videos were also produced that illustrate the development of the fruits. Figure 9a shows the transformation that occurs with the contour line of the fruits over time. Similarly, in Figure 9b, the change in the shape of the fruits can be observed. Finally, Figure 9c shows the evolution of the fruits' growth.

Figure 9

Three-dimensional fruit model
For model validation, 4 fruit samples were randomly selected. In each case, the process of tracing the edges and creating point vectors for the diameter and height was repeated. These vectors were compared with the data obtained from the ANNs. The mean difference of the points was of 12.975 mm for the radius and 11.560 mm for the height. Considering the natural variation in the fruits used for the model training, this results are consistent with what is expected of the model.

**Conclusion**

In this work, research on the growth of tomato fruits from the SM-16 hybrid was developed. For this purpose, an experiment was conducted in a greenhouse to collect data on the daily growth of the fruits. The mathematical and computational modeling of the data obtained experimentally was performed using computational simulations, primarily employing Octave software and Python programming language.

The adopted logistic growth model, adjusted to the found parameters and combined with the computational simulations, proved to be adequate for describing the growth behavior of the tomato fruits of the variety studied over time. Although the difference found at the end of the validation may be considered high, such difference can be justified by the fact that each tomato, even within the same variety, has its peculiarities, and also because a large amount of training data was considered, and the ANN used average values to create a standard model.

It is noteworthy that the research conducted is of high relevance to producers, as it assists them in identifying the development phases of their production. The model also allows the producer to compare the morphological characteristics of the fruits and their growth. In this way, the producer can more easily notice when something is abnormal. And when combined with agronomic knowledge, it is possible to identify the reasons why the production is not displaying the expected characteristics and address them before they can affect a larger part of the production. In summary, the model developed in this research work is relevant both for the producer and the consumer, as it enables the improvement of the physical appearance of the fruits, thus decreasing consumer dissatisfaction.

The possibility of adding more varieties of culture, or even having the same variety receive different treatments for possible comparisons, is highlighted. Another possible suggestion to be developed is the choice of another growth model in addition to the logistic, such as the Gompertz model frequently found in the literature. It would also be important to
analyze in more depth the aspects related to 3D printing, seeking to minimize the errors found.

**References**


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