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MODELING APPROACH FOR DETERMINING THE BIOLOGICAL AGE OF TOMATO FRUITS 'CV.SAVIOR' GROWN DURING THE WINTER

Tran Thi Dinh*, Tran Thi Lan Huong

Faculty of Food Science and Technology, Vietnam National University of Agriculture

Email: ttdinh@vnua.edu.vn*

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ABSTRACT

Tomato is a worldwide economic valuable and healthy crop with good nutritional properties. However, postharvest losses of tomato are relatively huge due to suboptimal harvest techniques and the maturity index. This issue could be solved if the biological variation of a tomato cultivar is quantified. In this study, a mathematical model was established to determine the biological age of tomato fruit cv 'Savior' grown during the winter. After which, the model was successfully validated using a single point estimation method. The model parameters estimated in this study could be used to predict the biological age of tomato grown in different locations and periods. The data play an important role for predicting the optimal harvest strategy in further research.

Keywords: Biological age, Fruit development, *Lycopersicon esculentum,* Modeling, Tomato, Ripening

Thiết lập mô hình toán học để xác định tuổi sinh học của quả cà chua giống savior trồng vụ đông

TÓM TẮT

Cà chua là một loại rau ăn quả được sử dụng rất phổ biến để ăn tươi cũng như làm nguyên liệu cho công nghiệp chế biến. Tuy nhiên tổn thất sau thu hoạch của cà chua khá cao do kỹ thuật thu hái và độ chín của cà chua khi thu hái chưa được tối ưu hóa. Vấn đề này có thể giải quyết nếu thông tin về dao động sinh học của quả cà chua được định lượng. Trong nghiên cứu này mô hình toán học được thiết lập nhằm xác định tuổi sinh học cho quả cà chua giống Savior trồng vụ đông. Tiếp theo, mô hình đã được kiểm định bằng phương pháp ước lượng điểm đơn và cho kết quả tốt. Các thông số của mô hình ước lượng trong nghiên cứu này có thể được dùng để dự đoán tuổi sinh học của giống cà chua này khi trồng ở các địa điểm và thời điểm khác nhau. Dữ liệu này đóng vai trò quan trọng trong nghiên cứu tiếp theo, cho phép xác định thời điểm thu hái tối ưu cho giống cà chua Savior trồng vụ đông.

Từ khóa: Cà chua, *Lycopersicon esculentum*, mô hình hóa, sự phát triển và chín của quả, tuổi sinh học.

1. INTRODUCTION

Tomato, *Lycopersicon esculentum* Mill, is a worldwide economically valuable and healthy crop with good nutritional properties. In Vietnam, tomato was first introduced about 100 years ago. The production area has been increasingly expanding in recent decades as tomato has become an important export crop. As a result, a farmer's income from tomato cultivation is 4-times higher than that from rice cultivating. Vietnam's tomato production area is about 15,000 - 17,000 ha with the yield ranging from 45 - 60 tons/ha (Tran Duc Vien, 2006).

Currently, there are two main types of tomato cultivars being cultivated in Vietnam: traditional heat sensitive cultivars and new heat tolerant cultivars. The latter are widely grown in the North of Vietnam as they are able to set fruit in high temperatures so the farmer can grow them both in winter and summer seasons. Among the heat tolerant cultivars, Savior is one of the most favored cultivars for its high yield performance, good appearance, and popularity among consumers.

Although tomato production is important in Vietnam and quality cultivars have been introduced, postharvest losses of tomato are still huge as farmers are unable to define the optimal picking time that ensures a good postharvest life of fruits. They mostly decide the picking time based on the date after anthesis and fruit color. However, fruit apperance only relatively describes the physiological maturity. Moreover, the color based classification of tomato ripeness used currently is discrete and subjective, and does not takes into account the biological variation of individual fruits in a batch. As a consequence, some fruits in a batch are harvested so early that they often fail to ripen while others are harvested so late they are unable to withstand being handled in the supply chain. Hence, there is an urgent need to find a method for predicting the optimal harvest time that is science-based and objective to meet the stringent retail demands for continuity of high quality products. A good approach for determining the biological age is crutial to build up a optimal harvest model for tomato fruit.

There have been some research groups using the biological age to classify the maturity of different fruits such as tomato (Hertog *et al.*, 2004), nectarines (Tijskens *et al.*, 2007; Rizzolo *et al.*, 2009), apple (Tijskens *et al.*, 2008, 2009). Recently, Van de Poel *et al.* (2012) expanded the biological age concept and used it to study other quality atributes of tomato (cv. Bonaparte) during development and ripening. In this study, we aimed to apply a similar approach to a larger population to determine the biological age of tomato fruit (cv. Savior).

2. MATERIALS AND METHODS

2.1. Plant material

Tomato seedlings (cv. Savior) were transplanted in the open field during the 2014 winter season at the Fruit and Vegetables Research Institute, Hanoi, Vietnam (21°00'38.9”N 105°55'39.2”E). From 300 randomly chosen plants, 700 tomato flowers were labeled on the plants shortly after anthesis across three labeling periods with 5-day intervals, each to cover wide range of fruit variation. Then, 360 individual fruits were selected to be monitored for color and diameter on the plants at three-day intervals during fruit development and two-day intervals during fruit ripening.

2.2. Experimental measurements

2.2.1. Fruit mass

Fruit diameter was monitored on-plant using a caliper (Mitutoyo, Japan). Fruit mass was calculated from fruit diameter and an average fruit density of 0.873 g/cm^3 as below:

$$m = V \times d = \frac{4}{3}\pi \times \left(\frac{D}{2}\right)^3 \times 0.873$$

where m: the fruit mass (g); V: the fruit volume (cm^3); D: the fruit diameter (cm); and d: the fruit density (g/cm^3)

2.2.2. Fruit skin color

The fruit skin color was measured on the same spot, at the equator of each fruit, using a Minolta CM-2500d colorimeter (Minolta Camera Co., Ltd, Osaka, Japan), and expressed in the CIELAB color space L*, a*, and b*. The fruit color was characterized in hue angle (°).

$$H = \arctan\left(\frac{b^*}{a^*}\right)$$

2.3. Model development

2.3.1. Fruit growth model

The change of fruit mass (*M (g)*) over time was modeled using the standard Gompertz growth model (Winsor, 1932) in its differential form (Eq. (1)):

$$\begin{cases} M(t) = M_{\max}.\exp(-C.\exp(-k_m.t)) \\ \dfrac{d}{dt}M(t) = k_m.M.\ln\left(\dfrac{M_{\max}}{M}\right) \\ M(0) = M_{\max}.\exp(-C) \end{cases} \qquad (1)$$

where k_m (d^{-1}): the growth rate; M_{max} (g): the maximum fruit mass; and C: a dimensionless displacement factor from the Gompertz function. These parameters were estimated from Eq. (1).

It was assumed that k_m and C were the variables whose values were generic for a specific cultivar while M_{max} was assumed to be different for every fruit. The Gompertz model was proven most suited given preliminary trials with several other growth models (Van de Poel *et al.*, 2012).

2.3.2. Color change model

Once a fruit has almost reached its maximum size, color change is triggered. Hue color change (measured as H in°) was described using a simple exponential decay model (Eq. (2)) which was implemented in its differential form:

$$\begin{cases} H(t) = H_{\min} + (H_O - H_{\min}).\exp(-k_h \times t) \\ \dfrac{d}{dt} H(t) = -(H - H\min).k_h \\ H(0) = H_o \end{cases} \quad (2)$$

where k_h (d^{-1}): the rate of color change; H_{min} (°): the minimum hue value; and H_o (°): the initial hue value. The parameters k_h, H_{min}, and H_o were assumed to be generic for a specific cultivar and were estimated from Eq. (2).

2.3.3. Biological switch model

The experimental data revealed that color change is only initiated after the fruit approachs its maximum size. By using the mass and color change data, the relationship between biological switch and the rate constant k_h is described by Eq. (3):

$$k_h = \frac{k_h^{\max}}{(1 + ((M_{\max} - M)/M_{\max}))^s} \quad (3)$$

where k_h^{max} (d^{-1}): the maximum rate of color change once fully triggered; and *s*: (dimensionless) defines the steepness of the switch and k_h^{max}. These two parameters were estimated using Eq. (3).

2.3.4. Biological age

The combination of fruit mass and fruit skin color is a good indicator of the biological age of an individual fruit. While the time of harvest only provides an arbitrary starting time point, biological age puts the experimentally measured values along a standardized time scale relative to a common development pattern. Biological age (t_{age} in d) is calculated from the experimental time values (t_{exp} in d, relative to the day of harvest) by adding a constant correction factor (Δt in d) following Eq. (4).

$$t_{age} = t_{\exp} + \Delta t \quad (4)$$

The correction factor Δt is a fruit specific factor. At harvest, $t_{exp} = 0$, $t_{age} = \Delta t$.

2.4. Model calibration using time series based data

The integrated models (Eqs. (1)-(4); with t being t_{age}) were calibrated using the dataset of color and mass collected during fruit development and ripening. The model parameters were estimated using OptiPa (Hertog *et al.*, 2007), a dedicated freeware optimization tool which was developed for use with Matlab (Matlab R2007b, The Math-Works, Inc., Natick, MA, USA). Based on the fruit mass data, common values for k_m, C; and fruit specific values for M_{max} và Δt were estimated. Then, based on the fruit skin color data, common values for k_h^{max}, H_{min}, H_o were estimated.

2.5. Model validation using single point estimation based data

Model validation using single point estimation was performed according to the procedure described by Van de Poel *et al.* (2012). The entire time series dataset, which was used to calibrate the model in the previous step, was artificially fractionated. The time series were broken apart and considered as 7857 individual points. Afterward, Δt values were estimated by the same analysis approach on the 7857 single observations. Finally, the resulting t_{age} values were compared to their t_{age} values obtained when calibrating the model.

3. RESULTS AND DISCUSSION

3.1. Change of mass during fruit development and ripening

The change of mass during fruit development and ripening is indicated in Figs. 1 - 3. All fruit followed an identical growth pattern. The initial growth process was slow and characterized mainly by cell division. Subsequently, cell expansion took place by which fruitlets grew faster mainly due to water uptake until some variable of maximal mass was reached. The development stage for Savior took about 50 - 52 d after anthesis. It was observed that different fruit reached a wide range of masses (from 30 g to 180 g) despite their similar flowering time. This can be explained by the fact that fruit are exposed to different microclimate conditions and sink/source relations within the plant (Van de Poel *et al.*, 2012). Therefore, M_{max} was estimated for every single fruit when calibrating the model.

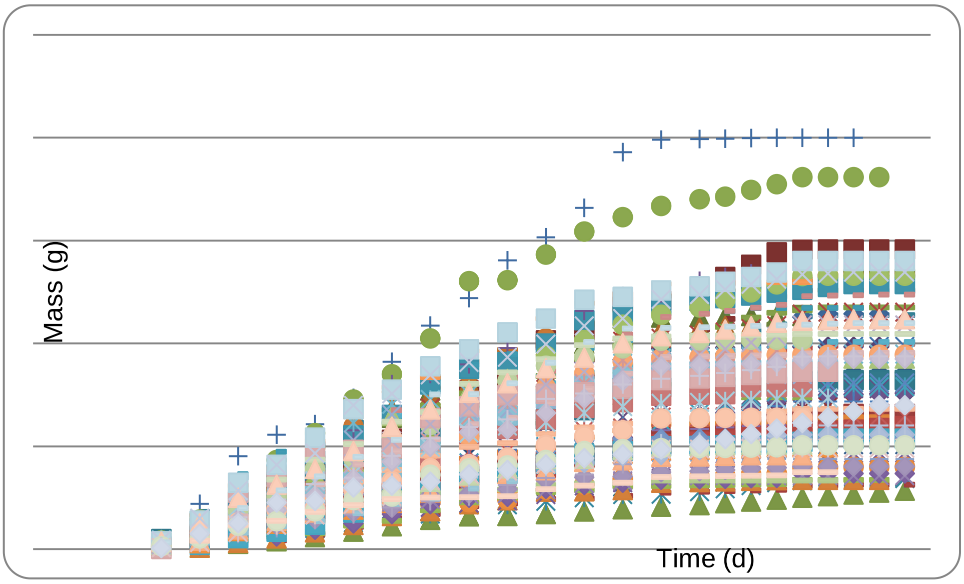

Fig. 1. Change of mass during fruit development and ripening (1st labeling period)

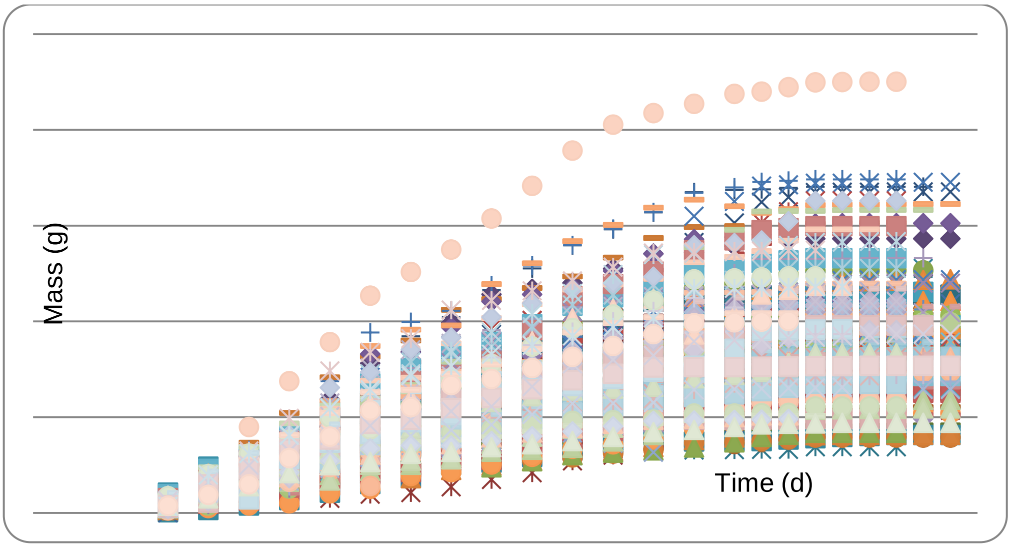

Fig. 2. Change of mass during fruit development and ripening (2nd labeling period)

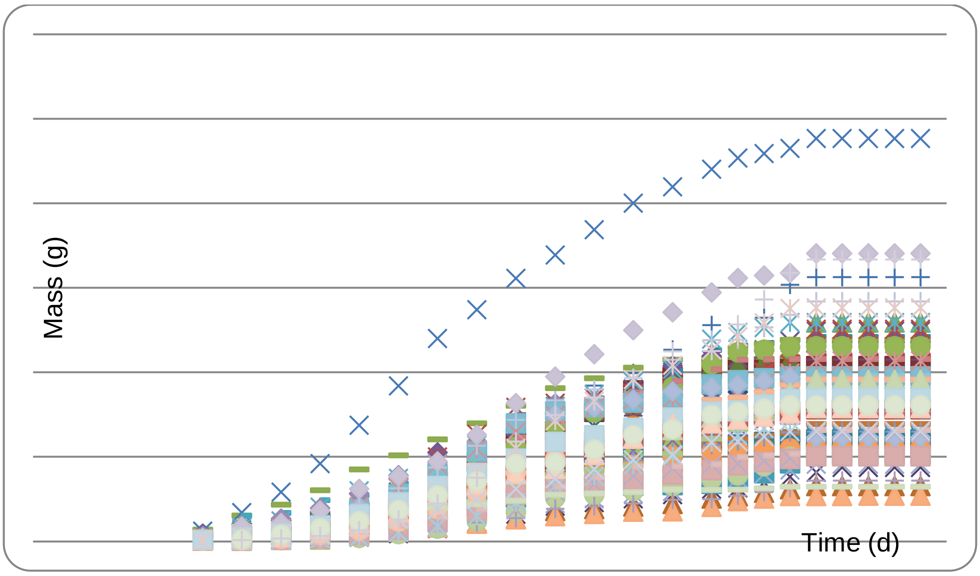

Fig. 3. Change of mass during fruit development and ripening (3rd labeling period)

3.2. Change of skin color during fruit development and ripening

The change of fruit skin color is illustrated in Figs. 4 - 6. During fruit development, there was no change of the hue value with the green fruit color being determined by chlorophyll. Color change was only triggered after the fruit approached its final mass. While mass remained almost constant, color dropped from immature green (hue ranging from 115° to 119°) down to mature red (hue ranging from 42° to 55°). Moreover, the color data revealed that there was a shift along the time axis among fruit, indicating that the biological age of individual fruits at the transition stage are not completely identical. Therefore, fruit specific values for Δt were estimated as well.

3.3. Model calibration using time series data

By using both mass and color data from the time series based dataset, the integrated model was calibrated by estimating the various model parameters. The goodness of fit is illustrated in Fig. 7. The generic parameters for the specific cultivar are given in Table 1, while the fruit specific parameters are given in Fig. 8.

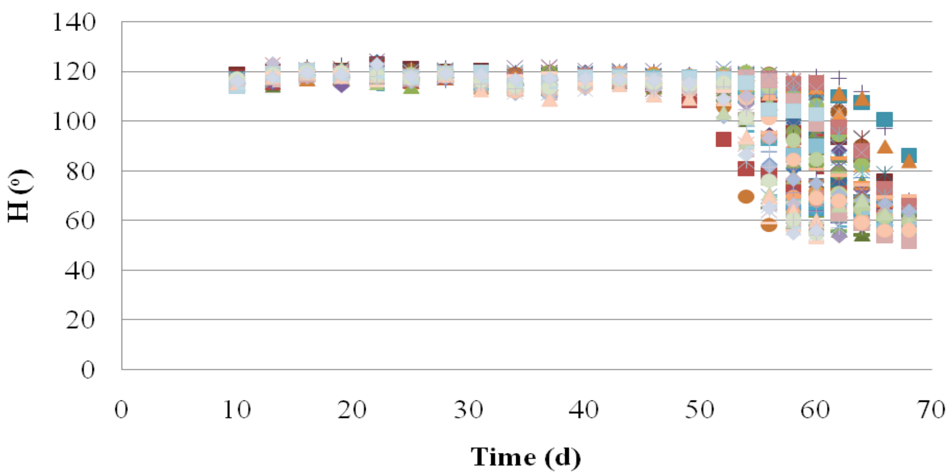

Fig. 4. Change of fruit color during fruit development and ripening (1st labeling period)

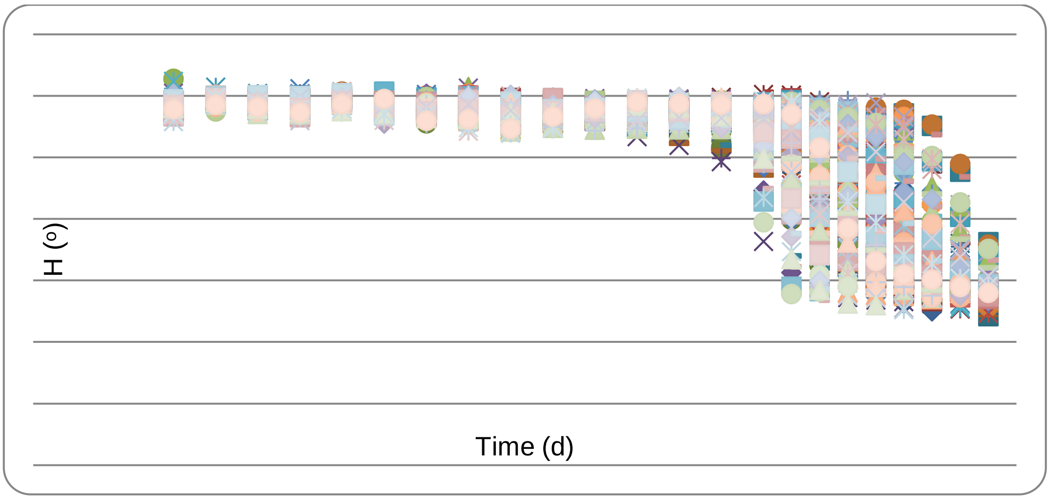

Fig. 5. Change of fruit color during fruit development and ripening (2nd labeling period)

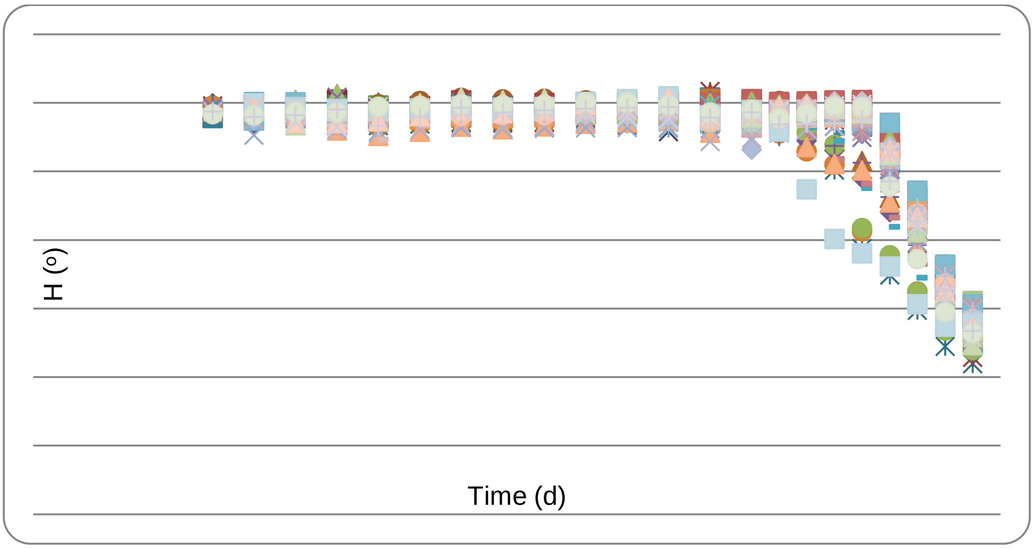

Fig. 6. Change of fruit color during fruit development and ripening (3rd labeling period)

Table 1. Parameter estimates for the calibration of the integrated model (Eqs. (1)-(4) fitted to the dataset of mass and color (n = 360)

Parameter	Estimate	Standard deviation
Growth model parameters		
C	6.54	0.05E-4
k_m (d^{-1})	0.0724	0.00004
Color change model parameters		
k_h^{max} (d^{-1})	80.38	4.79
H_o (°)	116.81	0.04
H_{min} (°)	58.19	0.16
Biological switch parameter		
s	73.22	0.67

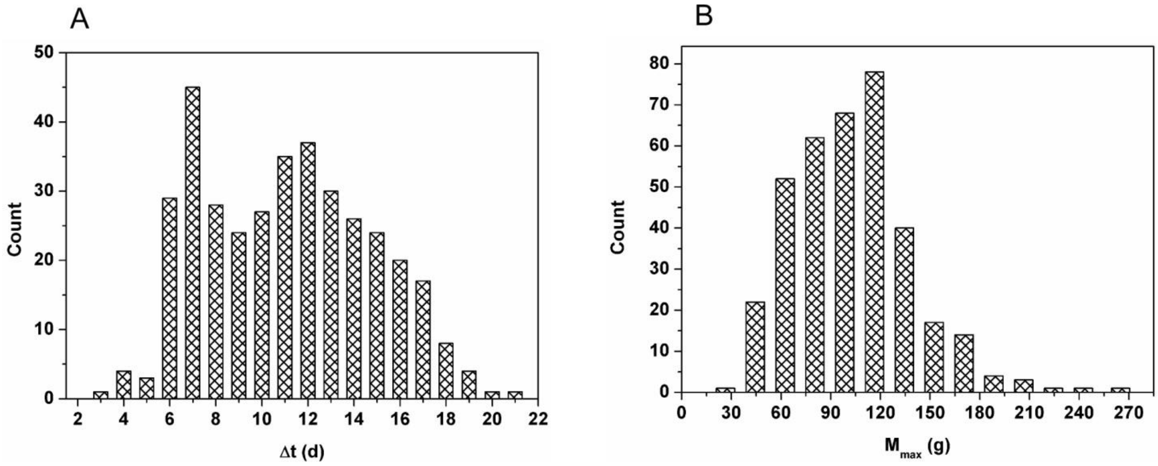

Fig. 7. Histograms showing A) the distributions of estimated Δt (d) for the 360 fruit from the dataset, and B) the distributions of estimated M_{max} (g) for the 360 fruit from the dataset

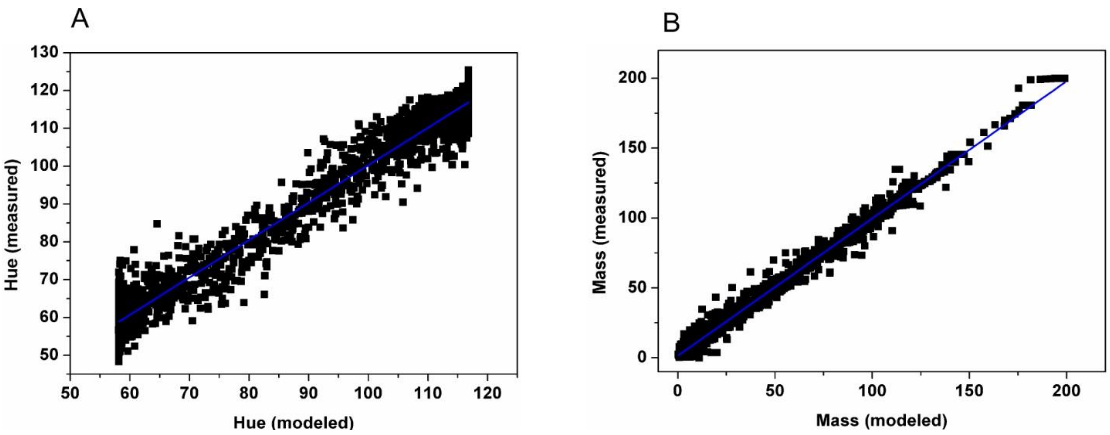

Fig. 8. A) Measured versus modeled color values, and B) Measured versus modeled mass values showing the goodness of fit for the integrated model, calibrated on the mass and color measurements of the dataset. The straight lines represent the line of perfect agreement between the modeled and measured values

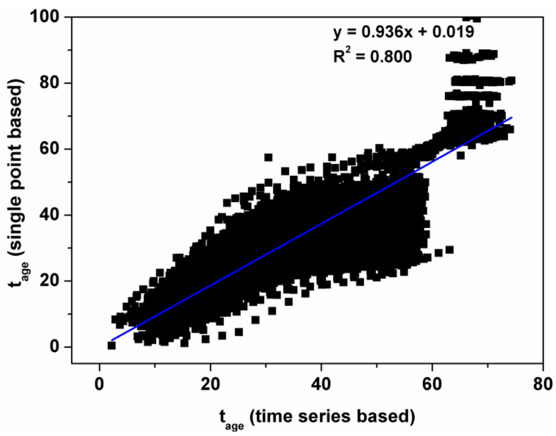

Fig. 9. Scatter plot showing the t_{age} (d) obtained by the time series based versus t_{age} (d) obtained by single point based

Fig. 7 shows that the overall fit of the model was good, the coefficients of determinations were 0.975 and 0.986 for color and mass, respectively, explaining about 98% of the observed variation in both fruit mass and hue color data. Data in Table 1 show that the generic parameters were estimated very accurately demonstrated by their small standard deviation. This was probably due to the large number of observations used (n = 360). When a comparison was made between the generic data obtained for Savior in this study and Bonaparte grown in a glass house in Belgium by Van de Poel *et al.* (2012), the standard deviation of some parameters such as C, k_h^{max}, and s for Bonaparte were higher than Savior as they had lower a number of observations (n = 60). Moreover, while both cultivars had similar magnitudes for most generic parameter estimates; Bonaparte had a higher value for s and lower values for k_h^{max} than Savior. The higher value of s means that the color change of Bonaparte is only triggered towards the end of the growth cycle. For k_h^{max}, a higher value was obtained for Savior (80.38 d^{-1}) than for Bonaparte (57.7 d^{-1}). This is because Savior was grown in an open field that gets more sunlight than Bonaparte grown in a glass house; hence, the rate of color change was higher. A similar phenomenon was observed for Savior grown at the same period in the net house (54.95 d^{-1}).

The distribution of the fruit specific parameters M_{max} and Δt are shown in Fig. 8. The maximum fruit mass M_{max} ranged from 26.5 g to 265 g with a mean of 93.91 ± 35.83 (g), confirming the broad range of fruit masses encountered (Figs. 1 - 3). The Δt ranged from 3 to 21 days with a mean of 10.60 ± 3.65 9 (d) (Fig. 8). From these findings, it can be concluded that the current approach can be applied for different tomato cultivars but it is necessary to estimate the generic parameters for each specific cultivar.

3.4. Model validation using single point estimate

Model validation using single point estimation was performed by fractionating the time series data into 7857 individual points; each was a combination of mass and hue value. Subsequently, using the same integrated models (Eqs. (1)-(4)) and fixed generic parameters, only the t_{age} values were estimated for 7857 observations. These t_{age} data were then compared with those obtained after rescaling the time series data using Eq. (4) and Δt for each fruit. The results are given in Fig. 9.

As the slope of the fitted line is 0.936, a high correlation between t_{age} was obtained between the time series based data and the single point based data. In addition, the coefficient of determinations was 0.8 for t_{age}, indicating that the fit was quite good. Eighty percent of the total variation in one variable can be explained by variation in the other variable. However, the fit still shows some deviations from the ideal 45° line, especially for bigger green fruits for which a good estimate of M_{max} is essential in order to obtain a good estimate of t_{age}, and for the fully red fruit, at which time one can no longer discriminate between fruits based on mass and/or color. The range in which the model works well is when fruit are either small or have undergone a color change, which is exactly the time all the postharvest sciences are interested in. In conclusion, the validity of the model was confirmed.

4. CONCLUSIONS

In this study, the changes in mass and skin color of 370 tomato fruits cv. 'Savior' grown during the winter season were monitored during fruit development and ripening. There were variations in color and especially in the masses of fruits having the same flowering time. The full measurement dataset was used to calibrate the model. Next, the model was successfully validated using a single point estimation method.

In further research, the calibrated model developed in the current study will be combined with data on quality changes of tomatoes during fruit development and ripening in order to build up a population model for predicting the optimal harvest date.

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