Australian Journal of Crop Science AJCS
AJCS 16(04):501-511 (2022) ISSN:1835-2707
doi: 10.21475/ajcs.22.16.04.p3464

Non-destructive estimation of tomato fruit properties by interactive consecutive model series

Murat KILIC*[1], M. Kadri BOZOKALFA[2]

[1]Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Ege University, Bornova, Izmir, Turkey
[2]Department of Horticulture, Faculty of Agriculture, Ege University, Bornova, Izmir, Turkey

*Corresponding author: kilic.murat@ege.edu.tr

Abstract

Fruit shape is an important quality parameter, and such variables as fruit diameter, height, weight, cross-sectional area and volume are components affecting this feature. In particular, these properties are the most important parameters in industrial applications for fruit grading, in determining the conditions of optimum packing, in providing the most suitable transportation facilities, and in optimizing crop production strategies. In this investigation, mathematical models were devised which enable estimation of the cross-sectional area, weight and volume of the fruit by a non-destructive method in the field before harvest. The modelling process was carried out by means of data analysis approaches and interactive consecutive calculation series for the Bandita F1 tomato cultivar. The correlation between the measured and estimated cross-sectional area, weight and volume of the fruit were 0.9672, 0.9809 and 0.9684, respectively. Apart from this, the accuracy rates of the models proposed for the estimation of the cross-sectional area, weight and volume are 97.12%, 95.40% and 95.37% respectively. In addition, the performance and validity of the models are in the “very good” category according to the all three analyses of NS, RSR and PBIAS. These results indicated that the models proposed gave high rates of accurate results.

Keywords: cross-sectional area, volume and weight of tomato fruit; interactive consecutive model series; mathematical modelling of fruit properties of tomatoes; non-destructive estimation of fruit properties; Bandita F1 tomato cultivar.

Introduction

The tomato (*Solanum lycopersicum* L.) belongs to the Solanaceae family and is the second most economically important vegetable crop in the world. Total worldwide tomato production is 182 million tons per annum, covering some 4 848 384 ha. China is the main producer of tomatoes followed by the USA, Turkey, India and Italy (FAOSTAT, 2019). Turkey has a yearly production of 8 414 920 t in open fields for fresh tomatoes, 3 735 080 t in open fields for processed tomatoes, and 3 888 555 t in greenhouses and low and high tunnels for fresh consumption (TUIK, 2019). Tomatoes are a significant horticultural commodity, widely used in the agro-food industry in a dried or processed form. Tomato fruits have a wide range of shapes and sizes, and include different cultivars, which are grown for fresh use and processing. Tomato quality parameters as evaluated by consumer preference are related to visual ratings such as external color and size, and these are used in fruit grading. Also, consumers mainly prefer fruits of equal weights and sizes (Shahbazi and Rahmati, 2013).
Crop modelling has a pivotal role in horticulture, and engineers use different models to solve practical problems of yield prediction (Wang et al., 2012), policy evaluation and process optimization (Gary et al., 1998). An agricultural product is frequently represented by its mass due to its relatively uncomplicated identity; however, volume-based sorting presents more valuable information than mass sorting (Ghazavi et al., 2013). Determination of the physical fruit properties of an agricultural product presents valuable information for handling, grading, packaging, and processing (Saracoglu and Ozarslan, 2015; Su et al., 2017). Furthermore, volume and surface area are of substantial importance for drying duration, and drying ratio, dimension features, mass, volume and surface and projection area are the most important design parameters for post-harvest equipment (Soltani et al., 2011).
A number of studies have been carried out to estimate the fruit properties for growth and development of muskmelon ovaries (*Cucumis melo* L.) (Jenni et al., 1997), the harvest size of pears (*Pyrus* spp.) (Williams et al., 1969), yield estimation in pecans (*Carya illinoinensis*) (Wright et al., 1990), and to monitor fruit growth and yield prediction (Mitchell, 1986; Jenni et al., 1997). Among physical characteristics, dimensions, mass, volume and projected areas are important parameters in sizing and grading systems which are based on mechanical, electrical and camera systems for apples (*Malus communis*), tomatoes (*Solanum lycopersicum* L.), peppers (*Capsicum annuum* L.), strawberries (*Fragaria vesca*), kiwi fruit (*Actinidia chinensis* var. *deliciosa*), and plums (Blasco et al., 2003; Lorestani and Tabatabaeefar, 2006; Moreda et al., 2009; Al-Mallahi et al., 2010; Kilic and Bozokalfa, 2010; Bozokalfa and Kilic, 2010; Clement et al., 2012; ElMasry et al., 2012; Zhang and Wu 2012; Arjenaki et al., 2013; Vivek et al., 2015; Fu et al., 2016; Quartezani et al., 2019). In addition, mass grading of fruit can reduce packaging and transportation costs (Khoshnam et al., 2007).

Several methods have been developed for the prediction of fruit volume or mass: water displacement (Mutschler et al., 1986; Radovich et al., 2004; Taheri-Garavand and Nasiri, 2010; Taheri-Garavand et al., 2011), geometrical attributes (Chakespari et al., 2010; Seyedabadi et al., 2011; Soltani et al., 2011), geometric dimension by optical measurements (Spreer and Müller, 2011) and image processing (Koc, 2007; Rashidi and Seyfi, 2008).

Physical properties have been used to determine fruit mass. Tabatabaeefar et al. (2000) used dimensions, volume and surface area to predict orange mass using a linear regression model. Tabatabaeefar and Rajabipour (2005) developed a quadratic equation to calculate apple mass. Shahbazi and Rahmati (2013) observed the physical properties of sweet cherry (*Prunus avium* L.) fruits and their relationships, and recommended that projected area be used to design and develop grading systems. Lorestani et al. (2014) determined a suitable model for predicting medlar fruit (*Mespilus germanica*) mass based on fruit length, width and thickness. The main purpose of such system and model studies is to sort the fruit based on its quality parameters, and volume-based sorting can provide a more efficient method than mass sorting (Rashidi and Seyfi, 2008). Furthermore, if the volume and weight of the fruit are known it is easy to compute the fruit density, and this measure for identifying the presence of hidden defects such as frost damage and internal damage to the mass of the fruit can be used to calculate the fruit density and to estimate maturity (Miller et al., 1988; Forbes and Tattersfield, 1999; Vivek et al., 2015). It is of prime importance to develop a system that is economically feasible and time efficient in order to provide results of high accuracy. Determining a relation between mass, dimension and projected area is useful and applicable in weight classification (Khanali et al., 2007), and these data present valuable information for the design of a commercial fruit sorter (Saracoglu and Ozarslan, 2015).

As knowledge is accumulated, results obtained from observation change from being qualitative to being quantitative, and mathematics can be adopted as a tool to express biological hypotheses. Advances in computer technology have made possible the consideration of the combined influence of several factors in various interactions (Oteng-Darko et al., 2013; Kilic, 2020; Kilic, 2018a; Kilic, 2018b; Kilic, 2018c).

The objective of this investigation was to devise models which allow estimation of the cross-sectional area, weight and volume of the fruit to be derived from the diameter at the beginning stage of the interactive consecutive solution process. The fruit diameter can be measured easily in a non-destructive way in the field before harvest. The Bandita F1 tomato cultivar was chosen for the modelling of fruit properties.

Results

Cross-sectional area of the tomato fruit

The model devised for estimation of the cross-sectional area of the fruit is given below. This process was carried out using data analysis approaches and interactive consecutive calculation series.

$M = 1.59257 * 10^2 * (1.14218 * 10^{-5})^{1/X}$

In the model, the variable *M* represents the cross-sectional area of the fruit in cm^2. The independent variable *X* represents the diameter of the fruit in cm in the model (Table 1). This measurement can be easily made in the field with a caliper on the number of fruits desired, in a short time and in a non-destructive way. Also, the fruits do not need to be picked for this process to be carried out. In other words, the fruit diameter can be measured in a non-destructive way before harvest.

In this investigation, fruit diameter was used as an independent variable at the initial stage of the interactive calculation process in the estimation of other properties of the fruit such as cross-sectional area, weight and volume in the field, in a non-destructive way and without harvesting.

The results of the models were recorded as numbers with two or three decimal places in accordance with the sensitivity of the measurement in the laboratory. This is also valid for the other stages in the solution of the models.

The three sample solutions for the model are represented below. The calculation process carried out for the other samples is the same as the ones for samples 5, 12 and 20 given below. The values of diameters in cm measured for samples 5, 12 and 20 are inserted in place of the variable *X* in the model. These data are given in Table 1 for all samples.

$M_5 = 1.59257 * 10^2 * (1.14218 * 10^{-5})^{1/6.158}$
$= 25.09\ cm^2$

$M_{12} = 1.59257 * 10^2 * (1.14218 * 10^{-5})^{1/6.639}$
$= 28.69\ cm^2$

$M_{20} = 1.59257 * 10^2 * (1.14218 * 10^{-5})^{1/7.532}$
$= 35.15\ cm^2$

The results of the model solution for the other samples are given in Table 1.

There was a 96.72% correlation between the values of the cross-sectional area of the fruits measured in the laboratory and those calculated by the model. The average difference between these values was 0.76 cm^2 as an absolute value, and 2.88% (Table 1). Figure 1 shows in detail the variation of the values of the cross-sectional areas measured in the laboratory and calculated by the model.

The values of the cross-sectional areas measured in the laboratory and those calculated by the model showed a similar trend for each sample level (Figure 1). The validity of the model devised to estimate the fruit cross-sectional area for the Bandita F1 was analyzed according to the different methods explained by Moriasi et al. (2007). These are: 1) Nash-Sutcliffe efficiency (NS), 2) Ratio of the root mean square error to the standard deviation of measured data (RSR), and 3) Percent bias (PBIAS) methods. When the results measured in the laboratory and obtained from the model solution were analyzed, values of NS=0.9356, RSR=0.2539 and PBIAS=-0.0003 were reached. The model performance fell into the ‘very good’ category in all of the three methods (Table 2).

Weight of the tomato fruit

The coefficient *R* for estimation of the fruit weight was obtained using the model given below. This coefficient represents the effects of the variables of fruit height, diameter and cross-sectional area on other variables modeled. The variable of the fruit height is represented by the coefficients in the formula below. This approach reduces the calculation intensity of the modeling process and increases the accuracy of the results. This procedure was carried out using data analysis approaches and interactive consecutive calculation series, as was stated previously.

$R = 1/(2.69419 * 10^{-1} - 2.7777 * 10^{-3} * M)$

In the model, the value of *R* is the coefficient obtained for estimation of the fruit weight. It does not have a unit. The variable *M* is the cross-sectional area of the fruit in cm^2,

Table 1. Comparison of the values of the cross-sectional area as measured in the laboratory and as calculated by the model.

Sample number	Diameter measured (cm) (X)	Cross –sectional area measured (cm^2)	Cross –sectional area calculated (cm^2) (M)	Difference (cm^2)	Difference as absolute value (cm^2)	Difference as absolute value (%)
1	6.087	25.35	24.56	0.79	0.79	3.13
2	6.143	24.40	24.98	-0.58	0.58	2.37
3	6.919	31.40	30.75	0.65	0.65	2.08
4	6.590	28.90	28.32	0.58	0.58	2.00
5	6.158	24.35	25.09	-0.74	0.74	3.04
6	6.101	25.20	24.66	0.54	0.54	2.14
7	6.340	27.65	26.46	1.19	1.19	4.31
8	6.269	23.60	25.93	-2.33	2.33	9.86
9	6.966	31.10	31.09	0.01	0.01	0.03
10	6.315	27.25	26.27	0.98	0.98	3.59
11	7.539	34.20	35.20	-1.00	1.00	2.92
12	6.639	27.80	28.69	-0.89	0.89	3.19
13	6.380	27.85	26.76	1.09	1.09	3.92
14	6.110	24.10	24.73	-0.63	0.63	2.61
15	6.732	29.10	29.37	-0.27	0.27	0.94
16	7.219	33.30	32.92	0.38	0.38	1.14
17	6.284	25.40	26.04	-0.64	0.64	2.51
18	6.053	23.35	24.30	-0.95	0.95	4.07
19	5.945	24.75	23.48	1.27	1.27	5.12
20	7.532	35.70	35.15	0.55	0.55	1.54
21	6.267	25.90	25.91	-0.01	0.01	0.04
Average					0.76	2.88
Correlation			0.9672			

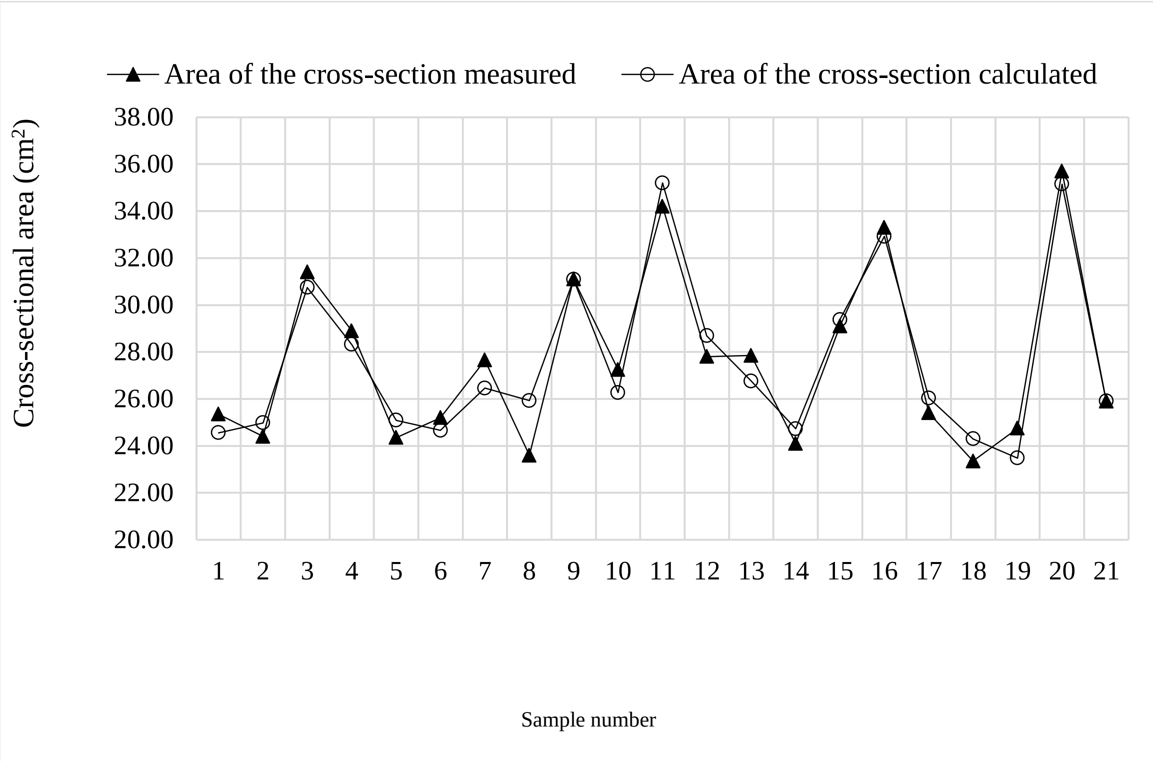

Figure 1. View of the cross-sectional area of the fruits as measured in the laboratory and as calculated by the model.

Table 2. Limit values and categories of model performance for the NS, RSR and PBIAS methods, in order to analyze model validity (Moriasi et al., 2007).

Performance rating	NS	RSR	PBIAS (%)
Very good	0.75<NS≤1.00	0.00≤RSR≤0.50	PBIAS<±10
Good	0.65<NS≤0.75	0.50<RSR≤0.60	±10≤ PBIAS<±15
Satisfactory	0.50<NS≤0.65	0.60<RSR≤0.70	±15≤ PBIAS<±25
Unsatisfactory	NS≤0.50	RSR>0.70	PBIAS≥±25

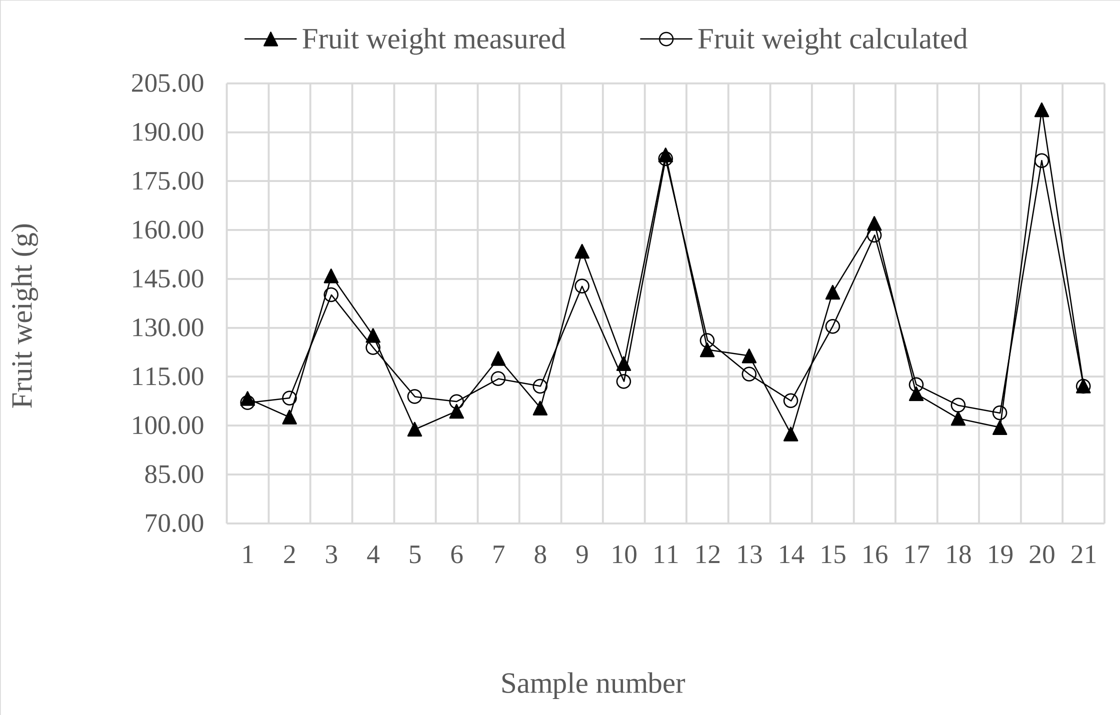

Figure 2. Graphical view of the fruit weight as measured in the laboratory and as obtained from the model solution.

determined for each sample in the previous stage (Table 1). The calculations of the coefficient *R* for the samples 5, 12 and 20 are given below.

$$R_5 = 1/(2.69419 * 10^{-1} - 2.7777 * 10^{-3} * 25.09) = 5.007$$

$$R_{12} = 1/(2.69419 * 10^{-1} - 2.7777 * 10^{-3} * 28.69) = 5.270$$

$$R_{20} = 1/(2.69419 * 10^{-1} - 2.7777 * 10^{-3} * 35.15) = 5.821$$

The calculation process was carried out similarly for the other samples. The coefficients *R* are given in Table 3 for all samples.

The model devised for estimation of the fruit weight is given below.

$$T = -1.54938 * 10^3 + 2.38019 * 10^2 * R + 1.16944 * 10^4/R^2$$

In the model, the variable *T* represents the weight of the fruit in g. *R* is the coefficient which was calculated for each sample in the previous stage (Table 3). The solutions for the sample fruits 5, 12 and 20 are given below.

$$T_5 = -1.54938 * 10^3 + 2.38019 * 10^2 * 5.007 + 1.16944 * 10^4/5.007^2 = 108.85\ g$$

$$T_{12} = -1.54938 * 10^3 + 2.38019 * 10^2 * 5.270 + 1.16944 * 10^4/5.270^2 = 126.09\ g$$

$$T_{20} = -1.54938 * 10^3 + 2.38019 * 10^2 * 5.821 + 1.16944 * 10^4/5.821^2 = 181.30\ g$$

The solutions for the other samples were carried out similarly. The weights of the fruits from the model solution for all samples are given in Table 4.

As seen in Table 4, there was a 98.09% statistical correlation between the values of the weight of the fruits measured in the laboratory and those obtained from the model solution. The average difference between these values is 5.70 g as an absolute value, and 4.60% (Table 4). The variation of the values of the fruit weight measured in the laboratory and those obtained from the model solution are shown in detail in Figure 2.

The weight of the fruit measured in the laboratory and that calculated by the model show a similar trend for each sample level (Figure 2). The validity of the model devised for estimation of the fruit weight of the Bandita F1 was verified in accordance with the three different methods explained by Moriasi et al. (2007). The values of NS, RSR and PBIAS obtained by these methods were 0.9393, 0.2464 and 0.7647 respectively. The model performance in this investigation fell into the 'very good' category according to all of the three methods (Table 2).

Volume of the tomato fruit

The model devised for estimation of the fruit volume is given below.

$$K = \frac{1.81325 * 10^2}{\left(1 + e^{4.64757*10^2 - 2.69514*T}\right)^{1/3.35242*10^2}}$$

In the model, the variable *K* represents the fruit volume in cm^3. *T* is the weight of the fruit which was calculated for each sample in the previous stage (Table 4). The *e* in the formula is the base of the natural logarithm, and its value was taken as 2.7182.

The solutions for the volumes of the sample fruits 5, 12 and 20 are given below.

$$K_5 = \frac{1.81325 * 10^2}{\left(1 + 2.7182^{4.64757*10^2 - 2.69514*108.85}\right)^{1/3.35242*10^2}} = 108.75\ cm^3$$

$$K_{12} = \frac{1.81325 * 10^2}{\left(1 + 2.7182^{4.64757*10^2 - 2.69514*126.09}\right)^{1/3.35242*10^2}} = 124.91 cm^3$$

$$K_{20} = \frac{1.81325 * 10^2}{\left(1 + 2.7182^{4.64757*10^2 - 2.69514*181.30}\right)^{1/3.35242*10^2}} = 181.32 cm^3$$

The solutions for the other samples were carried out similarly. The volumes of the fruits from the model are given in Table 5.

As seen in Table 5, the statistical correlation between the values of the volume of the fruits measured in the laboratory and those calculated from the model was 96.84%. The average difference between these values was 5.36 cm^3 as an absolute value, and 4.63% (Table 5). In order to show the variation of the volumes of the fruits measured in the laboratory and those obtained from the model solution in detail, these data are shown graphically in Figure 3.

The validity of the model devised for estimation of the fruit volume was verified in accordance with the methods of NS, RSR and PBIAS (Moriasi et al., 2007). The values obtained were 0.9311, 0.2624 and 0.5415 respectively. The model performance fell into the 'very good' category according to all of the three methods (Table 2).

Discussion

Many investigations have been carried out worldwide in order to estimate various physical properties of different fruits. In the present investigation, models have been devised for non-destructive estimation of cross-sectional area, volume and weight of the Bandita F1 tomato fruit. In this process, interactive consecutive solution methods have been used.

Mansouri et al. (2010) predicted the mass and surface area of pomegranate (*Punica granatum* L.) fruit by linear models using different physical properties. In the study, mass estimation using the fruit volume gave the best results. The models which simulate the shape of the fruit as spheroid and elliptic were found suitable for the solution process. In the present investigation, there was no need to simulate the shape of the fruit to another geometric form when estimating the fruit volume and mass. The shape of the fruit is taken into consideration in its natural form. Therefore, no deviation occurred in the modelling process due to the simulation of the fruit shape. The models proposed for estimation of the fruit weight and volume gave results with accuracy rates of 95.40% (Table 4, last column) and 95.37% (Table 5, last column) respectively. Yang et al. (2011) modelled the diameter of vine tomatoes by measuring with a VIS-NIR spectrophotometer and a digital caliper. The PLSR (Partial least squares regression) – BPANN (Back propagation artificial neural network) model gave the best result with R^2=0.88, RMSEP (Root mean square error of prediction) = 3.98 mm, and RPD (Residual prediction deviation) = 2.35. In the present investigation, the fruit diameter is measured non-destructively with a digital caliper, and the other properties of the fruit - cross-sectional area, volume and weight – are determined by interactive consecutive analysis series using the diameter of the fruit. This investigation has an innovative feature with this modelling and solution approach.

Shahbazi and Rahmati (2013) carried out mass modelling for sweet cherry (*Prunus avium* L.) using some physical properties of the fruit. Linear, quadratic, s-curve and power equations were used in the modelling process. The best results in the estimation of mass were obtained from the geometric mean diameter approach, and the value of R^2 was found to be 0.938. In the present investigation, the value of correlation between the measured and the estimated weights was found to be 0.9809 for the proposed model (Table 4). This result indicates that the proposed model estimates the fruit weight with a high rate of accuracy. Apart from this, it is in the "very good" category according to the NS, RSR and PBIAS performance and validity indicators (Table 6). Salihah et al. (2015) proposed a model for mass estimation of two varieties (Ledang (PO55) and Tambun (PO52)) of pomelo fruit (*Citrus grandis* L. Osbeck). In this process, the relationships between such physical properties of the fruit as mass, length, width, thickness, surface area, projected area and volume were used. The results indicated that the fruit mass had a significant level of statistical relationship at the 0.01 level with all the fruit properties above. In the present investigation, it was determined that the fruit weight, volume, cross-sectional area and fruit diameter have relationships with each other. These investigations are compatible with each other from this point of view.

Lee et al. (2017) predicted the volume of strawberries with a smartphone image processing technique. The value of R^2=0.8662 was obtained between the measured and the estimated fruit volumes. In the present investigation, 0.9684 correlation was obtained for the estimation of volume (Table 5). Apart from this, according to the model performance and validity indicators NS, RSR and PBIAS, the model proposed for the estimation of volume is in "very good" category (Table 6). Meyer et al. (2018) estimated volumes of the fruits of Roma tomatoes, salad tomatoes, white button mushrooms and strawberries using a machine vision system. Volumes of the fruits estimated by the optical imaging system were compared with the volumes obtained from the water displacement/buoyant force method. Equations were devised, which estimated the fruit volume using its weight. The value of R^2 was found to be higher than 0.92 between the volumes and weights of all the four types of fruits. In the present investigation, the models, which enable estimation of volume and weight of the fruit in a non-destructive way, take place in the "very good" category in all the three performance and validity indicators of NS, RSR and PBIAS (Table 6). Apart from this, the correlation between the measured and estimated weight and volume of the fruit were found to be 0.9809 (Table 4) and 0.9684 (Table 5) respectively. The models proposed in this investigation give the results with a high rate of accuracy.

Vivek et al. (2018) estimated the mass of the fruit of sohiong (*Prunus nepalensis* L.) using the quadratic, s-curve and power models. The fruits were separated into groups of small, medium and large, based on mass, in order to minimize the standard deviation. The most suitable mass model was obtained in quadratic form for the medium group with R^2=0.92. In the present investigation, 0.9809 correlation was obtained for the model proposed for estimation of fruit weight (Table 4). This model was also in the "very good" category according to the performance and validity indicators of NS, RSR and PBIAS (Table 6). Apart from this, there was no need to separate the fruits into such groups as small, medium and large, depending on their weights, in this process. The model devised is valid for all fruits of different sizes (Table 4, Figure 2). Khojastehnazhand et al. (2019) estimated the volume of apricots by an image processing technique. The value of R^2 was found to be 0.966 between the measured and the estimated volumes. In the present investigation, the correlation between the measured and the estimated volumes was 0.9684 (Table 5). Apart from this, in the model proposed, an image processing technique is not required. It is adequate to measure the diameter of the tomato fruits non-destructively in the field. Also, this estimation method does not necessitate an additional investment in the prediction of other fruit properties.

Jana et al. (2020) estimated volume and mass of potatoes, citrus and tomatoes by using image analysis technique. The accuracy rates for volume estimation of potatoes, citrus and tomatoes were 92.54%, 88.82% and 89.02% respectively, and for the estimation of mass were 92.98%, 89.31% and 88.56% respectively. In the present investigation, the accuracy rate of the model proposed for the volume estimation of tomatoes is 95.37% (Table 5, Figure 3), and the correlation between the measured volume and the estimated volume is 0.9684 (Table 5). Apart from this, the performance and validity of the model, which was proposed for the estimation of the volume of tomatoes, is in the "very good" class in all three analyses of NS, RSR and PBIAS (Table 6). These results indicate the accuracy and validity of the proposed model. In addition, the accuracy rate of the model proposed for the estimation of the weight of tomatoes is 95.40% (Table 4, Figure 2). Also, the correlation between the measured and estimated weight of the fruit is 0.9809 (Table 4). The performance and validity of the model for the estimation of the weight of tomatoes is in the "very good" category according to the three analyses of NS, RSR and PBIAS (Table 6). The results of this investigation indicate the accuracy and validity of the proposed models for estimation of both volume and weight of the tomato fruit.

Pathak et al. (2020) carried out mass modelling of Belleric Myrobalan (*Terminalia bellerica*) fruit in accordance with the basics of machine designing at post-harvest process. The fruits were separated into three groups according to their weight, of small, medium and large fruits. The power model represented the best fit for the medium group, while the quadratic model provided the most suitable fit for the small and large mass groups of fruits. In the present investigation, there is no need to sort the fruits according to their sizes in running the models devised for estimation of the fruit volume, weight and the cross-sectional area. The proposed models gave successful results for all the fruit parameters with different sizes. Al-Badri (2021) carried out volume estimation of tomato fruit using weight by linear regression. The value of R^2=0.8041 was obtained for the relationship between the fruit weight and the volume. In the next step, the value of R^2=0.5728 was obtained for the measured volume of the fruit and the estimated volume. In the present investigation, 0.9684 correlation was found between the actual fruit volume and the estimated volume (Table 5, Figure 3). These results show the accuracy and sensitivity of the model proposed for the estimation of tomato fruit volume. Nyalala et al (2021) carried out estimation of the mass and volume of tomato fruits using a machine-vision technique. In the prediction of mass, the value of R^2 was obtained as 0.971 by the Bayesian regularization artificial neural network approach, and the Gaussian method gave the best results in the estimation of volume with the value of R^2=0.982. In the present investigation, the correlation values of 0.9809 and 0.9684 were obtained for the models proposed for the estimation of weight and volume respectively (Table 4, Table 5). These results are close to the results of Nyalala et al. (2021). However, the models proposed in the present study are easier to run and this estimation approach does not need any investment.

All of these results indicate that the models proposed for estimation of the cross-sectional area, weight and volume of the tomato fruits give high rates of accurate results.

Evaluation of the methods for measurement of various properties of the fruit

The methods commonly used for measurement of the components enabling description of the fruit shape were evaluated from the points of view of practicality, length of measurement time, ease of use, reliability of results and cost of investment. Advantages of the models devised in this investigation were stated by taking into consideration the above criteria.

Measurement of cross-sectional area of fruit with a digital planimeter

As this method has a destructive feature, sample fruits cannot be used in marketing after the measurement process. This leads to yield and benefit loss depending on the number of sample fruits used in measurement. In order to obtain reliable results, each sample must be measured with at least in two repetitions. Running the device is a time-consuming process. Thus, as the number of sample fruits increases, the measurement period also lengthens.

Moreover, this method cannot be used in the field, and measurements must be performed in the laboratory, because the method is impractical under field conditions. In addition, as the use of the digital planimeter necessitates expertise, measurements must be carried out by technical personnel. Because of this, investment is necessary for the technical infrastructure.

Determination of the fruit weight

This variable is determined in the laboratory by a sensitive balance, and the measurement cannot be performed without the fruit being picked. Therefore, this method is impractical under field conditions. However, measurement of the fruit weight is not a time-consuming process, and the results of this method are reliable.

Determination of fruit volume by the water displacement method

Measurement of the fruit volume by the water displacement is easy to implement, and is a low cost method. On the other hand, it is a time consuming process, and impractical under field conditions.

Estimation of fruit volume by the image processing method

Computer vision systems and cameras are needed in the implementation of this method. Thus, investment is necessary for technical infrastructure. This process is easily understood by non-mathematicians. It can generally be extended and developed as required. No damage or destruction occurs on fruits tested. However, results from the method are not exact. Accuracy of the results increases statistically together with the increment in the number of

measurements performed. This means that all the results depend on estimation.
Sample fruits have to be harvested for the measurement, and this process must be carried out in the laboratory. The method is impractical under field conditions.

Determination of fruit diameter and height with a digital caliper
This method can be used easily under field conditions in a short time without damage or destruction of the fruit. Picking the fruit is not necessary. The method is practical for field conditions.

Estimation of fruit properties by modeling
The interactive models devised in this investigation are non-destructive. In this method, the variables which describe the shape of the fruit can be easily determined in the field in a short time, without the need to harvest the fruit. Therefore, this process is practical for field conditions.
No damage or destruction occurs to the fruit samples during the course of the measurement, and as it is not necessary to pick or harvest the fruit from the field, no yield or benefit loss occurs.
The models devised can easily be run by non-mathematicians. Results can be obtained in a short time with a scientific calculator or an MS Excel sheet on a computer. It is adequate to enter the diameter of the fruit into the model at the initial stage in order to run the interactive models in the description of the variables determining the shape properties of the fruit. The interactive models analyzing the weight, cross-sectional area, diameter and volume of the fruit can be run automatically as consecutive series. The diameter of the fruit, which is necessary in this process, can be easily measured with a caliper in the field in a non-destructive way on a number of sample fruits in a short time. The interactive models devised determine the cross-sectional area, weight and volume of the fruit from this variable in a short time. Because of this, no investment is needed for technical infrastructure. As the running of the model is not a time-consuming process, results are obtained in the field in a very short time. The fact that the method devised in this investigation is non-destructive and does not require the fruit to be picked allows all results to be obtained in the field before harvest in a very short time. Thus, the crop yield can be estimated reliably before harvest and also crop production strategies can be planned at an optimum level. The fact that the performance of the models devised fell into the 'very good' category for the three different verification methods shows that these models can be used reliably for the tomato cultivar used in the investigation.

Materials and methods

Plant materials
This investigation was carried out at the Departments of Agricultural Structures and Irrigation, and Horticulture of Ege University Faculty of Agriculture in Bornova, in Izmir Province. The experiment was conducted at a location of 38º28'N, 27º15' E and an altitude of 25 m, in order to examine the Bandita F1 cultivar. Fruits were harvested at the red maturity stage, and marketable fruits were used for evaluation.

Measurement of fruit properties
The diameter and height of the fruit was measured using a Mitutoyo (Kanawaga, Japan) digital caliper. Fruit height was measured from the blossom end to the top of the fruit, and the diameter was taken as the maximum diameter of the equatorial section. The cross-sectional area of the fruit was measured with a digital planimeter (Koizumi KP-90N, Japan) in accordance with the symmetry axis, by drawing the border of the cross-sectional area on paper and then measuring it with the digital planimeter. These variables are shown in Figure 4. Fruit weight was measured with Sartorius scales (Goettingen, Germany), and fruit volume was determined by the water displacement method (Kilic and Bozokalfa, 2010; Bozokalfa and Kilic, 2010) in the following way. Pure water was used, as the volume of 1 g of pure water is equal to 1 cm^3. First, a small outlet pipe was placed at a point on the same level as the surface of the pure water in Container 1. When a tomato fruit was put into Container 1 for volume measurement, the overflowing pure water drained into Container 2 by the outlet pipe. The weight of Container 2 was measured before receiving the pure water. Then the total weight of the drained pure water and Container 2 was measured. Thus, the exact weight of the drained pure water was determined by subtracting the weight of Container 2 from the total weight of the drained pure water and Container 2. This calculation process can be formulated as shown below.
WDPW = (C2+WDPW) - C2
where WDPW = weight of pure water drained from Container 1 into Container 2 (g); C2 = weight of Container 2 before receiving the drained pure water, in other words, the empty weight of Container 2 (g). Determination of tomato fruit volumes by the water displacement method is shown schematically in Figure 5.
Finally, the weight of the drained pure water from Container 1 was determined precisely. As the volume of 1 g pure water is equal to 1 cm^3, the exact volume of the tomato fruit could be determined correctly. Sartorius scales (Goettingen, Germany) were used in determining the weights. These are sensitive up to three decimal places.

Description of the models and application to the tomato fruit
Modeling is the use of equations or sets of equations to represent the behavior of a system. In effect, crop models are computer programs that mimic the growth and development of crops. A model simulates or imitates the behavior of a real crop by predicting the growth of its components, such as leaves, roots, stems and grains (Oteng-Darko et al., 2013). Simulation model development, testing and application demand the use of a large amount of technical and observational data supplied in given units and in a particular order. Data handling forces the modeler to resort to formal data organization and database systems (Oteng-Darko et al., 2013; Kilic, 2020; Kilic, 2018a; Kilic, 2018b; Kilic, 2018c). In this investigation, the modeling process was carried out by means of data analysis approaches and interactive consecutive calculation series. Mathematical models were devised which enable estimation of the cross-sectional area, weight and volume of the fruit by a non-destructive method in the field before harvest. The validity and performance of the models were analyzed by the methods of Nash-Sutcliffe efficiency (NS), the ratio of the root mean square error to the standard deviation of

Table 3. Values of the coefficient *R*, obtained for estimation of the fruit weights.

Sample number	Coefficient R	Sample number	Coefficient R
1	4.970	12	5.270
2	4.999	13	5.126
3	5.434	14	4.982
4	5.243	15	5.324
5	5.007	16	5.619
6	4.977	17	5.074
7	5.104	18	4.952
8	5.066	19	4.897
9	5.463	20	5.821
10	5.090	21	5.065
11	5.826		

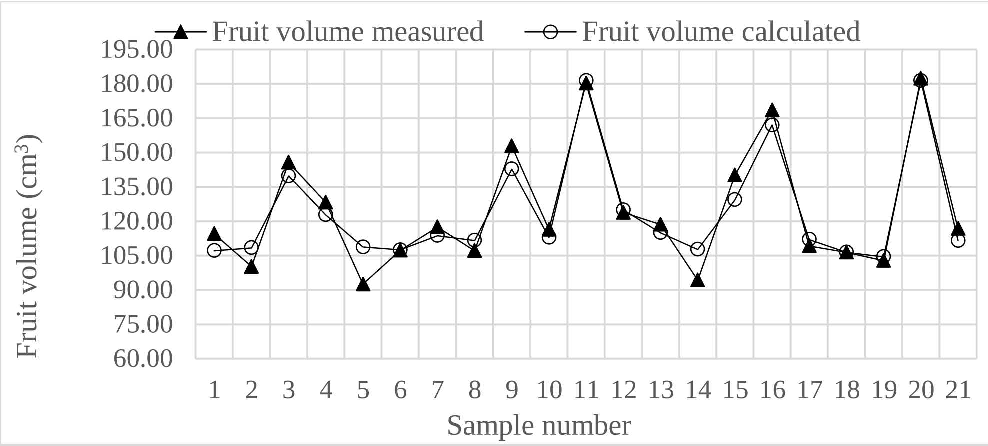

Figure 3. Graphical view of the fruit volume as measured in the laboratory and as obtained from the model solution.

Table 4. Comparison of the weights of the fruits measured in the laboratory and obtained from the model solution.

Sample number	Fruit weight measured (g)	Fruit weight calculated (g) (T)	Difference (g)	Difference as absolute value (g)	Difference as absolute value (%)
1	108.30	107.01	1.29	1.29	1.19
2	102.60	108.44	-5.84	5.84	5.70
3	145.95	140.09	5.86	5.86	4.02
4	127.60	123.94	3.66	3.66	2.87
5	98.85	108.85	-10.00	10.00	10.11
6	104.40	107.36	-2.96	2.96	2.84
7	120.60	114.37	6.23	6.23	5.16
8	105.40	112.08	-6.68	6.68	6.33
9	153.45	142.73	10.72	10.72	6.99
10	119.05	113.54	5.51	5.51	4.62
11	183.05	181.85	1.20	1.20	0.65
12	123.25	126.09	-2.84	2.84	2.30
13	121.40	115.75	5.65	5.65	4.65
14	97.40	107.59	-10.19	10.19	10.46
15	140.95	130.41	10.54	10.54	7.48
16	162.00	158.42	3.58	3.58	2.21
17	109.75	112.55	-2.80	2.80	2.55
18	102.20	106.20	-4.00	4.00	3.91
19	99.40	103.88	-4.48	4.48	4.50
20	196.90	181.30	15.60	15.60	7.92
21	112.10	112.01	0.09	0.09	0.08
Average				5.70	4.60
Correlation	0.9809				

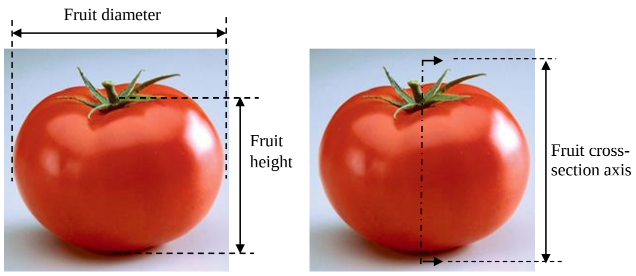

Figure 4. Definitions of the fruit height, the maximum diameter of the equatorial section, and the cross-sectional axis of the fruit.

Table 5. Comparison of the volumes of the fruits measured in the laboratory and those obtained from the model solution.

Sample number	Fruit volume measured (cm^3)	Fruit volume calculated (cm^3) (K)	Difference (cm^3)	Difference as absolute value (cm^3)	Difference as absolute value (%)
1	114.55	107.16	7.39	7.39	6.45
2	100.20	108.40	-8.20	8.20	8.18
3	145.70	139.80	5.90	5.90	4.05
4	128.25	122.78	5.47	5.47	4.27
5	92.55	108.75	-16.20	16.20	17.50
6	107.25	107.46	-0.21	0.21	0.19
7	117.50	113.69	3.81	3.81	3.24
8	107.15	111.61	-4.46	4.46	4.16
9	152.80	142.80	10.00	10.00	6.55
10	116.45	112.93	3.52	3.52	3.02
11	180.25	181.32	-1.07	1.07	0.60
12	123.80	124.91	-1.11	1.11	0.90
13	118.60	114.95	3.65	3.65	3.07
14	94.25	107.65	-13.40	13.40	14.22
15	140.10	129.33	10.77	10.77	7.69
16	168.55	162.00	6.55	6.55	3.89
17	109.25	112.03	-2.78	2.78	2.55
18	106.40	106.46	-0.06	0.06	0.05
19	102.80	104.49	-1.69	1.69	1.64
20	182.40	181.32	1.08	1.08	0.59
21	116.80	111.55	5.25	5.25	4.49
Average				5.36	4.63
Correlation	0.9684				

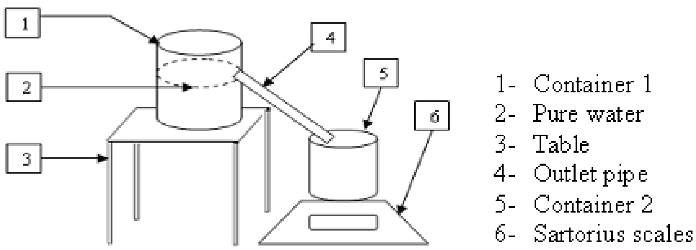

Figure 5. Determination of tomato fruit volume by the water displacement method.

Table 6. Results of the validity and performance analysis of the models devised for estimation of the cross-sectional area, weight and volume of the fruit.

	Method I		Method II		Method III	
Fruit features	NS	Model validity	RSR	Model validity	PBIAS	Model validity
Fruit cross-sectional area	0.9356	Very good	0.2539	Very good	-0.0003	Very good
Fruit weight	0.9393	Very good	0.2464	Very good	0.7647	Very good
Fruit volume	0.9311	Very good	0.2624	Very good	0.5415	Very good

measured data (RSR), and percent bias (PBIAS) (Moriasi et al., 2007).

Conclusions

Fruit shape is an important quality parameter. The weight, volume and cross-sectional area of the fruit are important components, especially in industrial applications of fruit grading, in constituting the optimum packing conditions and in providing the most suitable transportation facilities. Different approaches are used in estimating the volume, weight and cross-sectional area of the fruit, and methods which are based on interactive solution techniques also give reliable results, as in this investigation. In particular, nonlinear model approaches play an important role in reaching these results. Solutions which analyze the diameter, height, weight, cross-sectional area and volume of the fruit have the advantages of being faster, reliable, non-destructive and more practical.

In this investigation, the size of the cross-sectional area, weight and volume of the fruit are reached from the diameter at the initial stage of the interactive calculation series. The diameter is a property of the fruit which is easily measurable non-destructively in the field before harvest. The modelling process provides an important advantage from the points of view of practicability and the reliability of the solutions reached.

The validity of the models devised for estimation of the cross-sectional area, weight and volume of the fruit for the Bandita F1 tomato cultivar were verified in accordance with the three different methods explained by Moriasi et al. (2007) (Table 6).

These results show that the models devised for estimation of the fruit properties of tomatoes as described above can be used with a high level of accuracy.

As a research tool, model development and implementation can contribute to identifying gaps in our knowledge, thus enabling more efficient and targeted research planning. An intensely calibrated and evaluated model can be used to effectively conduct research that in the end saves time and money and significantly contributes to developing sustainable agriculture that meets the world's needs for food (Oteng-Darko et al., 2013; Kilic, 2020; Kilic, 2018a; Kilic, 2018b; Kilic, 2018c).

References

AL-Badri SBS (2021) Determine the tomatoes volume. Proceeding of the 2nd international conference on agriculture, food security and safety, Vol. 2, 2021, pp. 76-82. ISSN 2682-7158. DOI: https://doi.org/10.32789/agrofood.2021.1007

Al-Mallahi A, Kataoka T, Okamoto H, Shibata Y (2010) Detection of potato tubers using an ultraviolet imaging-based machine vision system. Biosystem Engineering. 105: 257-265.

Turkish Statistical Institute (2019) TUIK [online] Website: https://biruni.tuik.gov.tr/bitkiselapp/bitkisel.zul [02/2019]

Arjenaki OO, Moghaddam PA, Motlagh AM (2013) Online tomato sorting based on shape, maturity, size, and surface defects using machine vision. Turkish Journal of Agriculture and Forestry. 37: 62–68.

Blasco J, Aleixos N, Molto E (2003) Machine vision system for automatic quality grading of fruit. Biosystem Engineering. 85: 415–423.

Bozokalfa MK, Kilic M (2010) Mathematical modeling in the estimation of pepper (*Capsicum annuum* L.) fruit volume. Chilean Journal of Agricultural Research. 70 (4): 626-632.

Chakespari GA, Rajabipour A, Mobli H (2010) Mass modeling of two apple varieties by geometrical attributes. Australian Journal of Agricultural Engineering. 1: 112-118.

Clement J, Novas N, Gazquez J A, Manzano-Agugliaro F (2012) High speed intelligent classifier of tomatoes by colour, size and weight. Spanish Journal of Agricultural Research. 10: 314–325.

ElMasry G, Cubero S, Molto E, Blasco J (2012) In-line sorting of irregular potatoes by using automated computer-based machine vision system. Journal of Food Engineering. 112: 60–68.

Food and Agriculture Organization of the United Nations (2019). FAOSTAT [online] Website http://www.fao.org/faostat/en/#data/QC [02/2019]

Forbes KA, Tattersfield GM (1999) Estimating fruit volume from digital images. IEEE Africon. 1: 107–112.

Fu L, Sun S, Li R, Wang S (2016) Classification of kiwifruit grades based on fruit shape using a single camera. Sensors. 16 (7): 1012 doi:10.3390/s16071012

Gary C, Jones JW, Tchamitchian M (1998) Crop modelling in horticulture: State of the art. Scientia Horticulturae. 74: 3–20.

Ghazavi MA, Karami R, Mahmoodi M (2013) Modeling some physico-mechanical properties of tomato. Journal of Agricultural Science. 5: 210-223.

Jana S, Parekh R, Sarkar B (2020) A De novo approach for automatic volume and mass estimation of fruits and vegetables. Optik - International Journal for Light and Electron Optics. 200: 163443. https://doi.org/10.1016/j.ijleo.2019.163443

Jenni S, Stewart KA, Bourgeois G, Cloutier DC (1997) Nondestructive volume estimation for growth analysis of eastern-type muskmelon ovaries. HortScience. 32: 342-343.

Khojastehnazhand M, Mohammadi V, Minaei S (2019) Maturity detection and volume estimation of apricot using image processing technique. Scientia Horticulturae. 251: 247–251. https://doi.org/10.1016/j.scienta.2019.03.033

Khoshnam F, Tabatabaeefar A, Varnamkhasti MG, Borghei A (2007) Mass modeling of pomegranate (P*unica granatum* l.) fruit with some physical characteristics. Scientia Horticulturae. 114 (1): 21-26.

Kilic M (2020) A new analytical method for estimating the 3D volumetric wetting pattern under drip irrigation system. Agricultural Water Management. 228 (2020) 105898. https://doi.org/10.1016/j.agwat.2019.105898

Kilic M (2018a) Analytical description of the wetting pattern in a drip irrigation system by a new method, simultaneous double parabola design. I: Method. 1st International Congress on Agricultural Structures and Irrigation. Antalya, Turkey. 365-375.

Kilic M (2018b) Analytical description of the wetting pattern in a drip irrigation system by a new method, simultaneous double parabola design. II: Application. 1st International Congress on Agricultural Structures and Irrigation. Antalya, Turkey. 376-385.

Kilic M (2018c) 3D movement of water in soil at drip irrigation system and mathematical description of the wetting pattern by a new method. Ege University Scientific Research Project: ID 975 (2016-ZRF-060).

Kilic M, Bozokalfa MK (2010) Volume modeling of different types of pepper fruits with some physical characteristics. Journal of Food, Agriculture & Environment. 8 (3&4): 360-368.

Koc AB (2007) Determination of watermelon volume using ellipsoid approximation and image processing. Postharvest Biology and Technology. 45: 366-371.

Lee DH, Cho Y, Choi JM (2017) Strawberry volume estimation using smartphone image processing. Horticultural Science and Technology. 35(6):707-716.

Lorestani AN, Gawhari S, Sadi S (2014) Mass modeling of common medlar (*Mespilus germanica*) fruit with some physical characteristics. Universal Journal of Agricultural Research. 2 (3): 97-100 doi: 10.13189/ujar.2014.020303

Lorestani AN, Tabatabaeefar A (2006) Modeling the mass of kiwi fruit by geometrical attributes. International Agrophysics. 20: 135–139.

Miller WM, Peleg K, Briggs P (1988) Automatic density separation for freeze-damaged citrus. Applied Engineering in Agriculture. 4 (4): 344–348.

Mansouri YS, Khazaei J, Beygi SRH, Mohtasebi SS (2010) Statistical modeling of Pomegranate (*Punica granatum* L.) fruit with some physical attributes. J Food Process Technol. 1:1. DOI: 10.4172/2157-7110.1000102

Meyer AC, Eifert J, Wang H, Sanglay G (2018) Volume estimation of strawberries, mushrooms, and tomatoes with a machine vision system. International Journal of Food Properties. 21:1, 1867-1874. https://doi.org/10.1080/10942912.2018.1508156

Mitchell PD (1986) Pear fruit growth and the use of diameter to estimate fruit volume and weight. HortScience. 21: 1003-1005.

Moreda, GP, Ortiz-Cañavate J, García-Ramos FJ, Ruiz-Altisent M (2009) Non- destructive technologies for fruit and vegetable size determination – a review. Journal of Food Engineering. 92: 119–136.

Moriasi DN, Arnold JG, Van Liew MW, Binger RL, Harmel RD, Veith TL (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE. 50 (3): 885–900.

Mutschler MA, Yasamura L, Sethna J (1986) Estimation of tomato fruit volume from fruit measurements. Report of the Tomato Genetics Cooperative. 36: 10.

Nyalala I, Okinda C, Chao Q, Mecha P, Korohou T, Yi Z, Nyalala S, Jiayu Z, Chao L, Kunjie C (2021) Weight and volume estimation of single and occluded tomatoes using machine vision. International Journal of Food Properties. Vol. 24, no. 1, 818–832. https://doi.org/10.1080/10942912.2021.1933024

Oteng-Darko P, Yeboah S, Addy SNT, Amponsah S, Owusu Danquah E (2013) Crop modeling: A tool for agricultural research – A review. Journal of Agricultural Research and Development. Vol. 2(1). pp. 001-006. Available online http://www.e3journals.org. SSN: 2276-9897

Pathak SS, Pradhan RC, Mishra S (2020) Mass modeling of Belleric Myrobalan and its physical characterization in relation to post-harvest processing and machine designing. J Food Sci Technol. 57(4):1290–1300. https://doi.org/10.1007/s13197-019-04162-1

Quartezani WZ, Souza Lima JS, Pletsch TA, Oliveira EC, Berilli SS, Mantoanelli E, Posse RP, Suci LM (2019) Multiple linear and spatial regressions to estimate the influence of Latosol properties on black pepper productivity. Australian Journal of Crop Science. 13(06):857-862. doi: 10.21475/ajcs.19.13.06.p1424

Radovich TK, Kleinhenz MD, Honeck NJ (2004) Important cabbage head traits and their relationships at five points in development. Journal of Vegetable Crop Production. 10: 19-32.

Rashidi M, Seyfi K (2008) Modeling of kiwi fruit mass based on outer dimensions and projected areas. American-Eurasian Journal of Agricultural & Environmental Sciences. 3: 26-29.

Salihah BN, Rosnah S, Norashikin AA (2015) Mass modeling of Malaysian varieties Pomelo fruit (Citrus grandis L. Osbeck) with some physical characteristics. International Food Research Journal. 22(2): 488-493.

Saracoglu T, Ozarslan C (2015) Kiraz domatesi meyvesinin kütle ve hacminin matematiksel modellenmesi. Journal of Adnan Menderes University Agricultural Faculty. 12 (1): 103-108 (in Turkish with an abstract in English).

Seyedabadi E, Khojastehpourb M, Sadrniab H, Saiedirad MH (2011) Mass Modeling of Cantaloupe Based on Geometric Attributes: A Case Study for Tile Magasi and Tile Shahri. Scientia Horticulturae. 130: 54-59.

Shahbazi F, Rahmati S (2013) Mass modeling of sweet cherry (Prunus avium l.) fruit with some physical characteristics. Food and Nutrition Sciences. 4: 1-5. http://dx.doi.org/10.4236/fns.2013.41001

Soltani M, Alimardani R, Omid M (2011) Modeling the main physical properties of banana fruit based on geometrical attributes. International Journal of Multidisciplinary Sciences and Engineering. 2: 1-6.

Spreer W, Müller J (2011) Estimating the mass of mango fruit (Mangifera indica cv. Chok Anan) from its geometric dimensions by optical measurement. Computers and Electronics in Agriculture. 75: 125-131.

Su M, Ye Z, Zhang B, Chen K (2017) Ripening season, ethylene production and respiration rate are related to fruit non-destructively-analyzed volatiles measured by an electronic nose in 57 peach (Prunus persica L.) samples. Emirates Journal of Food and Agriculture. 29 (10): 807-814. doi: 10.9755/ejfa.2017.v29.i10.696

Tabatabaeefar A, Rajabipour A (2005) Modeling the mass of apples by geometrical attributes. Scientia Horticulturae. 105: 373–382.

Tabatabaeefar A, Vefagh–Nematolahee A, Rajabipour A (2000) Modeling of orange mass based on dimensions. Journal of Agricultural Science and Technology. 2: 299-305.

Taheri-Garavand A, Nassiri A (2010) Study on some morphological and physical characteristics of sweet lemon used in mass models. International Journal of Environmental Sciences. 1: 580-590.

Taheri-Garavand A, Rafiee S, Keyhani A (2011) Study on some morphological and physical characteristics of tomato used in mass models to characterize best post harvesting options. Australian Journal of Crop Science. 5(4): 433-438.

Vivek K, Mishra S, Pradhan RC (2018) Physicochemical characterization and mass modelling of Sohiong (Prunus nepalensis L.) fruit. Journal of Food Measurement and Characterization.12:923–936. https://doi.org/10.1007/s11694-017-9708-x

Vivek VG, Iqbal SM, Gopal A, Ganesan D (2015) Estimation of volume and mass of axi-symmetric fruits using image processing technique. International Journal of Food Properties. 18: 608–626.

Wang J, Gao S, Yuan J, Ma F (2012) Simulation of dry matter accumulation, partitioning and yield prediction in processing tomato (Lycopersicon esculentum Mill.). Australian Journal of Crop Science. 6(1):93-100.

Williams MW, Billingley HD, Batjer LP (1969) Early season harvest size prediction of Barlett pear. Journal of the American Society for Horticultural Science. 94: 596-598.

Wright GC, Storey JB, Harris MK, Sprinz PT (1990) Preharvest pecan yield estimation. HortScience. 25: 698-700.

Yang H, Kuang B, Mouazen AM (2011) Size estimation of tomato fruits based on spectroscopic analysis. Advanced Materials Research. Volume 225-226, Issue 1-2, pp 1254-1257.

Zhang YD, Wu LN (2012) Classification of fruits using computer vision and a multiclass support vector machine. Sensors. 12: 12489–12505.