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MATHEMATICAL MODELING IN THE ESTIMATION OF PEPPER (*Capsicum annuum* L.) FRUIT VOLUME

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ABSTRACT

Peppers (*Capsicum annuum* L.) are an important horticultural crop and are used fresh and processed. Fruit size estimation is used to describe the fruit's growth curve, monitor individual plant growth, predict yield, and conduct physiological studies. Water displacement techniques are used to determine fruit volume, but these are time-consuming and impractical under field conditions. The aim of this study was to devise a mathematical model to analytically determine the non-destructive pepper fruit volume. Fruit volume was described as a dependent variable, while length, weight, and diameter were independent variables in the model which was formulated as Yi = 19.226859 + 0.139562 Xi – 0.256142 Zi + 1.429122 Ti, where Yi = fruit volume (cm^3), and Xi, Zi, and Ti are fruit diameter (mm), length (mm), and weight (g) , respectively. This equation can be easily used to predict the accuracy of pepper fruit volume. A significant relationship ($P \leq 0.01$) was found between dependent and independent variables. The correlation coefficient describing the relationship between the actual fruit volumes and the model solution was 0.9516. Consequently, it was determined that pepper fruit volume can be described as depending on fruit length, weight, and diameter.

Key words: *Capsicum annuum*, fruit growth, modeling applications, pepper fruit, predicting, water displacement.

INTRODUCTION

Peppers (*Capsicum annuum* L.) are important among vegetable crops throughout the world. Pepper pods have a wide variety of shapes, sizes, colors, and include many different varieties of hot and sweet peppers. Peppers are widely processed, particularly sweet red conical peppers which are mainly used for paste, while hot and sweet red peppers are used in the spice industry (Da Costa *et al.,* 2006; Bozokalfa *et al.,* 2009; Costa *et al.,* 2009).

Fruit weight, length, and diameter are important quality traits in many horticultural crops and are used in genetic diversity studies (Do Rego *et al.,* 2003). Fruit volume estimation is used to estimate pecan (*Carya illinoinensis*) yield (Wright *et al.,* 1990), growth and development of muskmelon (*Cucumis melo*) ovaries from anthesis to fruit maturity (Jenni *et al.,* 1997), and pear harvest size (*Pyrus* spp.) (Williams *et al.,* 1969). Measuring fruit size allows fruit growth and growth curve monitoring, and yield prediction (Mitchell, 1986; Jenni *et al.,* 1997). Leaf lamina area is estimated from leaf length and width and can be used for blueberry (*Vaccinium angustifolium*) cultivar selection (NeSmith, 1991). Fruit traits or plant growth curves may be used to predict yield, and the fruit expression rate may be used to estimate susceptibility to diseases and physiological defects (Ngouajio *et al.,* 2003). Volume may be used to calculate density to indicate cabbage (*Brassica oleraceae* L. var. *capitata*) head maturity (Isenberg *et al.,* 1975; Radovich *et al.,* 2004). Pre-harvest estimation of head weight may be used to compare head size for both breeding purposes and physiological studies in globe artichokes (*Cynara scolymus* L., Düzyaman and Ünver Düzyaman, 2005). Fruit volume is important in horticultural crop processing and volume measurement by water displacement is time-consuming and impractical under field conditions. Several research studies have been conducted to predict fruit volume or weight (Currence *et al.*, 1944; Mitchell, 1986; Jenni, 1997; Düzyaman and Ünver Düzyaman, 2005; Demirsoy and Demirsoy, 2007). A non-destructive method using fruit length, diameter, and weight could be precisely and rapidly applied.

Models representing different fruit parameters have usually been described with linear equations (Assaf *et al.,* 1982; Mitchell, 1986; Russo, 1996; Jenni *et al.,* 1997;

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Ngouajio *et al.,* 2003). Ngouajio *et al.* (2003) determined the correlation coefficients of bell pepper volume as 0.24 to 0.65. Their results show that more variables have to be simultaneously taken into consideration in order to describe specific fruit features. In addition, the relationships between the various fruit parameters have to be described in nonlinear modeling systems. The aim of this process is to more accurately describe relationships between different fruit parameters. Various types of models have also been devised for different purposes related to food and agricultural applications (Müller *et al.,* 2008; Pulido *et al.,* 2008; Aranda-Sánchez *et al.,* 2009; Sirisomboon and Kitchaiya, 2009).

There has been limited research about the estimation of pepper fruit volume, so the objective of this study was to devise an accurate mathematical model to analytically determine the volume of whole pepper fruits using the relationships between fruit weight, diameter, and length.

MATERIALS AND METHODS

This study was carried out in three main stages, namely the field experimental process, laboratory measurements, and modeling applications. The processes carried out in each stage are given below.

Field experiment

Experiments were conducted in sandy loam soil in the Department of Horticulture, Faculty of Agriculture of Ege University in Bornova (38º28' N, 27º15' E, 25 m.a.s.l.), Izmir Province, Turkey. Seeds in the experiments were sown in soil under low tunnels for seedling production on 10 March 2008. On 15 April (5 wk after sowing, 3-4 leaf stage), seedlings were transplanted to the nursery and spaced 40 x 75 cm. Soil preparation, fertilization, plant protection, and other growing practices were the ones usually employed for pepper cultivation in Turkey (Vural *et al.,* 2000). Sweet pepper cv. Yalova yaglık, the most widely found in processing, was employed in the experiment. This cultivar is characterized by fruit which are thick-walled, conical-shaped, dark green when immature, and red at maturity. They are mainly exploited at the red mature stage.

Laboratory measurement processes

At harvest, 45 edible fruits were chosen covering a wide range of sizes. Fruit diameter and length were measured with digital calipers (Mitutoyo, Kanawaga, Japan, accuracy ± 0.01 mm). Fruit length was measured from the end of the blossom to the top of the shoulder, while fruit diameter was measured at the widest point of the fruit shoulder (Russo, 1996; Ngouajio *et al.,* 2003). Fruit weight was measured with scales (Sartorius, Goettingen, Germany, accuracy ± 0.001 g). Pure water was employed in this study to determine the actual volume of the pepper fruit since the volume of 1 g pure water is equal to 1 cm^3. First, a small drainpipe was placed at the level of the pure water in container-1. When a pepper fruit was put in container-1 to measure volume, the overflowing pure water was drained with the drainpipe into container-2. The weight of container-2 was measured before adding the pure water. Then, the total weight of the drained pure water and container-2 was measured with Sartorius scales. 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 plus container-2. This calculation process can be formulated as:

$$\text{WDPW} = (\text{C2} + \text{WDPW}) - \text{C2} \qquad [1]$$

where WDPW = weight of drained pure water from container-1 into container-2 (g) and C2 = weight of container-2 before receiving drained pure water, i.e., weight of empty container-2 (g).

Finally, WDPW from container-1 was precisely determined by this process. Since the volume of 1 g of pure water is equal to 1 cm^3, the exact volume of the pepper fruit could be correctly determined. A scale, sensitive to the third decimal (Sartorius, Goettingen, Germany), was employed to determine weights.

Modeling process

In the model design process, fruit volume was described as a dependent variable (Yi), and fruit diameter, length, and weight were described as independent variables with the symbols Xi, Zi, and Ti, respectively. The general structure of the model, according to Zero Origin, can be described by Equation [2]:

$$Yi = a + b^* Xi + c^* Zi + d^* Ti \qquad [2]$$

where Yi = fruit volume (cm^3); a = fixed term in the model; Xi = fruit diameter (mm); Zi = fruit length (mm); Ti = fruit weight (g); b, c, and d represent the coefficients for fruit diameter, length, and weight functions, respectively. In order to determine the value of parameters a, b, c, and d in the model, four first-degree equations were obtained, including four unknown variables. These equations were then solved by the Cramer Method (Bronson, 2006).

The validity of the model was tested in the next research stage. For this purpose, the relationship between the dependent variable fruit volume and the independent fruit diameter, weight, and length variables was determined. In order to perform this process, the value of the Multiple Determination Coefficient (r^2), as explained by Green and

Margerison (1978), and Spiegel and Stephens (1998), was determined. This calculation is shown by Equation [3]:

$$r^2 = (b\sum x_i y_i + c\sum z_i y_i + d\sum t_i y_i)/\sum y_i^2 \qquad [3]$$

Values of all parameters in Equation [3] were calculated according to the Mean Origin axis. In the next stage, the value of the Corrected Multiple Determination Coefficient $(r')^2$, as explained by Green and Margerison (1978), was calculated. Thus, the effect of each added new parameter on the model was analyzed. The significance of r^2 was determined by the F Test.

In the last stage of the research study, actual fruit volume was compared with the calculated volume from the model solution for each fruit sample. In addition, differences between these two data were determined as a percentage and the correlation coefficient was calculated.

RESULTS AND DISCUSSION

The length, weight, and diameter of the 45 randomly chosen sample fruits from the harvested yields at the end of the field experiment are shown in Figure 1. Fruit length, weight, and diameter values have an irregular distribution with a wide range (Figure 1). Some descriptive statistical parameters of the fruit samples are given in Table 1.

In the model design process, functional relationships between fruit length, weight, diameter, and volume were described by the model in Equation [2].

Values of parameters a, b, c, and d were calculated by executing the process explained in the Methods section. They were 19.226859, 0.139562, -0.256142, and 1.429122, respectively. The model describing fruit volume depends on fruit length, weight, and diameter in accordance with these results is shown below:

$$Yi = 19.226859 + 0.139562Xi - 0.256142Zi + 1.429122Ti$$

Differences in volume of sampled fruit (Table 2) varied between 0 and 10% in 77.77% of the samples

Table 1. Some descriptive statistical features of the pepper fruit samples.

	Length	Diameter	Weight
	mm		g
Arithmetic mean	106.77	52.28	71.53
Variance	165.59	95.06	258.12
Median	108.20	51.30	69.83
Standard deviation	12.87	9.75	16.07
Minimum	52.60	39.20	44.69
Maximum	133.20	103.90	109.21

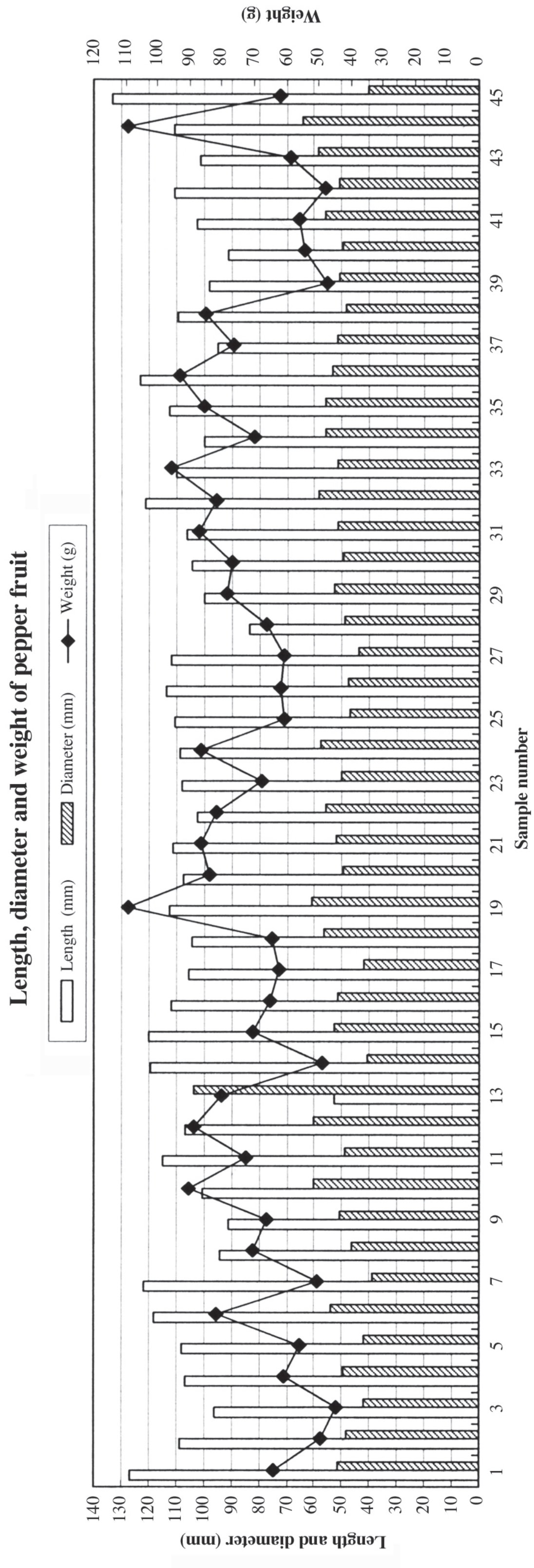

Figure 1. Length, weight, and diameter values of 45 pepper fruit samples randomly chosen at harvest.

Table 2. Comparison of measured and model solution pepper fruit volumes.

Sample number	Measured volume	Model solution	Difference	Sample number	Measured volume	Model solution	Difference
	cm³		%		cm³		%
1	92.25	85.40	7.42	24	117.98	123.04	-4.29
2	75.57	69.28	8.32	25	75.53	84.56	-11.95
3	65.18	64.38	1.22	26	86.17	84.83	1.55
4	75.24	85.52	-13.65	27	85.71	83.78	2.26
5	76.25	77.46	-1.59	28	113.14	99.53	12.02
6	122.27	113.54	7.14	29	106.91	113.02	-5.72
7	60.55	65.42	-8.04	30	101.85	109.85	-7.86
8	105.16	102.25	2.76	31	125.61	124.15	1.16
9	103.41	97.32	5.89	32	111.91	113.30	-1.24
10	134.86	131.16	2.74	33	130.91	134.99	-3.12
11	119.28	100.49	15.75	34	101.97	101.15	0.80
12	142.73	127.34	10.78	35	111.58	120.68	-8.16
13	124.74	135.02	-8.24	36	128.56	128.26	0.24
14	58.47	64.21	-9.80	37	106.36	111.65	-4.97
15	90.15	96.25	-6.78	38	119.65	119.50	0.12
16	91.07	90.50	0.63	39	81.52	69.28	15.02
17	79.07	87.05	-10.10	40	76.48	80.52	-5.28
18	89.69	92.35	-2.97	41	88.65	80.82	8.83
19	160.51	154.99	3.44	42	75.92	66.64	12.22
20	115.03	118.96	-3.42	43	89.44	85.34	4.58
21	115.34	121.89	-5.68	44	166.75	155.71	6.62
22	103.02	117.33	-13.89	45	67.08	78.92	-17.66
23	93.45	95.31	-1.99				

showing the distribution in Table 3. Measured volume and model solution showed similar trends (Figure 2).

In order to determine the relationship in the model between the dependent variable fruit volume and the independent fruit length, weight, and diameter variables, r^2 was calculated (0.9055). This result showed that fruit volume could be described according to the fruit length, weight, and diameter parameters. In addition, $(r')^2$ was calculated (0.8986) in order to analyze the effect of each new parameter on the model. It was determined that the addition of a new parameter to the model did not increase result accuracy under these conditions since $(r')^2$ was lower than r^2.

Table 3. Distribution of pepper fruit samples according to volume difference.

Volume difference interval	Number of samples	Ratio
%		%
0 - 5	20	44.44
5.1 - 10	15	33.33
10.1 - 15	7	15.56
15.1 - 20	3	6.67
Total	**45**	**100**

The significance of r^2 was analyzed with the F test. Results show that there is a highly significant ($P \leq 0.01$) relationship between the dependent variable fruit volume and the independent fruit length, weight, and diameter variables. Furthermore, the correlation coefficient describing the relationship between the actual fruit volumes and the model solution was 0.9516.

Volume is an important yield trait (Kalloo and Bergh, 1993) in horticultural crops and may be predicted with cabbage head volume in many commercial fields and in an experimental area (Kleinhenz, 2003). Estimation of mean fruit size is important to meet quality standards, increase market value, monitor fruit growth, predict fruit yield, and sort fruits (Wilhelm *et al.*, 2005). Radovich and Kleinhenz (2004) indicate that volume measurements by water displacement techniques are time-consuming and impractical, some formulae observed in several fruits and vegetables are obtained from some fruit properties

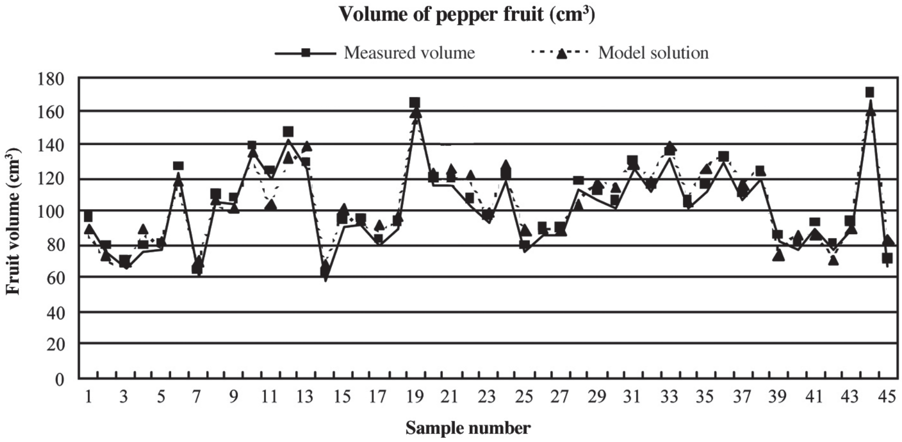

Figure 2. Measured and model solution pepper fruit volumes.

such as fruit length, height, and weight. Estimation of fruit volume is mainly related with fruit shape and a strong relationship is reported for tomato (Mutschler *et al.,* 1986), cucumber (Marcelis, 1992), cabbage (Radovich and Kleinhenz, 2004), and peach (*Prunus persica*) (Demirsoy and Demirsoy, 2007). Measuring fruit size allows monitoring fruit growth and growth curves (Jenni *et al.,* 1997).

In order to estimate bell pepper fruit volume, Ngouajio *et al*. (2003) applied linear modeling techniques and proposed a new nondestructive estimation model for bell pepper. The correlation coefficients were 0.24, 0.66, and 0.65 for different linear equations.

The objective of this research study was to devise a mathematical model to analytically determine the volume of conical pepper fruit through fruit traits. Volume in the model was described as a dependent variable and fruit length, weight, and diameter as independent variables. At the end of the field experiments, laboratory measurements, and mathematical analysis processes, the model was described in the following way:

$$Yi = 19.226859 + 0.139562Xi - 0.256142Zi + 1.429122Ti$$

where Yi = fruit volume (cm^3); a = fixed term in the model; Xi = fruit diameter (mm); Zi = fruit length (mm); and Ti = fruit weight (g).

The significance of r^2 was analyzed by the F test. Results showed that there was a significant ($P \leq 0.01$) relationship between dependent and independent variables in the model. Furthermore, the correlation coefficient describing the relationship between the actual fruit volumes and the model solution was 0.9516.

Several research studies have been carried out to estimate volume more easily than the water displacement technique. The comparison between predicted volume using sphere and spherical formulae and the determination of actual volume calculated in cabbage allowed concluding that the spherical ellipsoid formula could be the most accurate and precise. Furthermore, formulae-based estimates of volume required less than 1 min compared to 5 min for water displacement (Radovich and Kleinhenz, 2004). Fruit volume can be estimated with an image processor. Hahn and Sanchez (2000) observed new algorithms to predict the volume of non-regular shaped fruits more easily than by conventional methods in carrot, whereas Koc (2007) determined volume by ellipsoid approximation and image processing is a simple method to estimate watermelon volume. However, further studies will be needed to get accurate nondestructive models for different pod shapes of pepper fruit and processed vegetables.

CONCLUSIONS

A wide range of pepper fruit was evaluated in this study and the volume of conic pepper fruit was estimated by a model containing three fruit traits, which highly improved model accuracy of estimation of fruit volume, because the model consisted of three fruit traits. The proposed model observed a high correlation (0.9516) coefficient between actual fruit volume and model results. In addition, results from the model solution were significant ($P \leq 0.01$). The general equation obtained from this research could be practical in the estimation of conic-type pepper fruit volume and applicable under field conditions. Consequently, data revealed from actual studies indicated that such modeling approaches could be applied in the estimation of various types of pepper fruit, whereas further studies are required to allow accurate volume estimation of other non-geometrically shaped horticultural crops.

RESUMEN

Modelos matemáticos en la estimación del volumen de fruto de pimiento (*Capsicum annuum* L.). Los pimientos (*Capsicum annuum* L.) son cultivos hortícolas importantes y su fruto es usado fresco y procesado. La estimación del tamaño de fruto se usa para describir la curva de crecimiento del fruto, monitoreo individual de crecimiento vegetal, predicción de rendimiento, y estudios fisiológicos. Las técnicas de desplazamiento de agua son usadas para determinar volumen de fruto pero consumen tiempo y no son prácticas en terreno. El objetivo de esta investigación fue idear un modelo matemático para determinar analítica y no destructivamente el volumen del fruto de pimiento. En el modelo se describió volumen del fruto como variable dependiente, y longitud, peso y diámetro de fruto como variables independientes. El modelo se formuló como Yi = 19.226859 + 0.139562 Xi – 0.256142 Zi + 1.429122 Ti, donde Yi es volumen de fruto (cm^3), y Xi, Zi y Ti son diámetro (mm), longitud (mm) y peso (g) del fruto respectivamente, y esta ecuación puede ser fácilmente usada para predecir confiablemente el volumen del fruto. Se encontró una correlación significativa ($P \leq 0,01$) entre las variables dependientes e independientes. El coeficiente de correlación que describe la relación entre volumen real del fruto y aquel del modelo fue 0,9516. Consecuentemente, se determinó que el volumen del fruto del pimiento puede depender de su longitud, peso y diámetro.

Palabras clave: *Capsicum annuum*, crecimiento de fruta, aplicaciones de modelación, pimiento, predicción, desplazamiento de agua.

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