Modeling rupture force based on physical properties – a case study for roma tomato (*Solanum lycopersicum*) fruits

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Abstract: Biophysical properties of agricultural materials are important in designing of processing machines. In this study, some physical properties of tomato (*Solanum lycopersicum*) fruits were determined and their mutual relationships were studied. Dimensions (major diameter, minor diameter, and length), mass, volume, fresh and dry matter weight, as well as rupture point under uniaxial loading were measured. Other properties, including Poisson's ratio, modulus of elasticity, energy for rupture, density, arithmetic mean diameter, geometric mean diameter, diameter of equivalent volume sphere, and sphericity were calculated accordingly. Statistical analysis of the data indicated significant correlations between the rupture force and fresh weight, volume, dry weight, major diameter, minor diameter, arithmetic mean diameter, geometric mean diameter, and diameter of equivalent volume sphere. Fruit volume had significant correlations with fresh weight and average diameter. Correlations between major and minor diameters were very significant in this variety. Finally, regression equations were developed to model tomato biophysical properties.

Keywords: correlation, elasticity, geometry, mechanical properties, rupture

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1 Introduction

Modelling of the physical properties of agricultural materials in pre-harvest, harvest, and post-harvest operations is helpful in quality monitoring which is an important factor in marketing (Arazuri et al., 2007; Nesvadba et al., 2004; Terdwongworakul, 2016). Physical properties of agricultural materials are valuable as they are needed to predict the quality and behavior of products, while these properties aid understanding of food processing dynamics (Jahangiri et al., 2016; Nesvadba et al., 2004).

Designing automated harvesters, processing, sorting, and packaging equipment required the knowledge of physical properties of agricultural materials (Alamar et al., 2008; Gholami et al., 2012; Li et al., 2011). In a study, some physical properties of tomato were measured and their correlations were determined, however no model was presented to determine those properties (Sirisomboon et al., 2012).

In case of tomatoes, it has been reported that knowledge of these properties can help to avoid tomato losses due to handling and transportation (Babarinsa and Ige, 2012). In regard to the potential advantage of tomato production for export, appropriate sorting and transportation of the product is important which necessitates knowledge of the bio-physical properties of tomatoes. In this study, some physical properties of tomato fruits (*Solanum lycopersicum* ‘Early Ch’) were determined and modelled.

2 Materials and methods

A sample of 117 tomato fruits (Early Ch, Canyon, Italy) were used in the experiment. The tomatoes had been cultivated in the greenhouse of Tarbiat Modares

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University, Tehran, Iran (35.74^{o}N, 51.16^{o}E). Mass, M (g), of each fruit was measured using a 0.01 g precision balance (KBJ 650-2NM precision balance, KERN, Germany) immediately after harvesting. Three mutually perpendicular dimensions (i.e. length (L), major diameter (D_1), and minor diameter (D_2) all in mm) were also measured using a 0.01 mm digital caliper. Radial compression force was applied between two parallel plates using a material testing machine (STM-20, SANTAM, Iran) equipped with a S-Beam load cell (DBBP-100, Bongshin, Korea) at a loading rate of 10 mm min^{-1}. Mechanical properties including rupture force, extension at rupture point and rupture energy were calculated using the data obtained from the material testing machine.

Among the physical properties, fruit density, ρ (g cm^{-3}), arithmetic mean diameter, D_a (mm), geometric mean diameter, D_g (mm), diameter of equivalent volume sphere, D_V (mm), and sphericity, ψ (dimensionless), were calculated using the following equations (Equations (1) to (5)) (Figura and Teixeira, 2007).

$$\rho = \frac{M}{V} \tag{1}$$

$$D_a = \frac{D_1 + D_2 + L}{3} \tag{2}$$

$$D_g = \sqrt[3]{D_1 \times D_2 \times L} \tag{3}$$

$$D_V = \sqrt[3]{\frac{6 \cdot V}{\pi}} \tag{4}$$

$$\psi = \frac{D_g}{L} \tag{5}$$

where, V is volume (cm^3).

Firmness or hardness is an important mechanical property of fruits that is used for quality evaluation in terms of sensitivity to injury and damage that must be taken account during harvesting, handling, sizing and transportation of crops (Yilmaz and Yildirim, 2016). Rupture occurs at a certain point where the material can no longer sustain the applied load. At this point, extension continues without increasing stress ($\frac{d_\sigma}{d_\varepsilon} = 0$) (Figura and Teixeira, 2007). If the stress-extension diagram was substituted with force-extension diagram, rupture force can also be defined as the first extremum of the diagram in that the rate of compression force change with respect to extension is equal to zero ($\frac{d_F}{d_x} = 0$).

Reaching material rupture requires a specific amount of energy, E_R (in N mm) which is defined as the area under the force-extension diagram starting at the origin (extension=0 and force=0), to the rupture point where the maximum compression force (F_R) is measured (in N). Equation (6) was suggested for estimating the energy required at the rupture point (Beer et al., 2009).

$$E_R = FR \times x_a \tag{6}$$

where, x_a is the average extension from the start to rupture point (mm)

Modulus of elasticity was also measured (Sirisomboon et al., 2012) (Equation (7)) as a physical property that is often used as a parameter to evaluate mechanical behavior of fruits under static loading (Jahangiri et al., 2016).

$$ME = 9.81\sqrt{1.125(1-P^2)^2 \frac{F_R^{\ 2}}{D3\left(\frac{x_a}{10}\right)}} \tag{7}$$

where, ME is modulus of elasticity (N mm^{-2}); P is Poisson's ratio ($P = \frac{0.5M + 0.1(100 - M)}{100}$ (dimensionless); M is average moisture content of tomatoes (dimensionless); D is the equatorial diameter of the fruit (cm).

3 Results

Based on the test results, the force that the tomato sample can tolerate, up to the rupture point, was about 57.85±9.14 N that occurs at an extension of 10.52± 1.44 mm requiring 271.70±83.31 N mm of energy. The average mass and volume of tomatoes were obtained to be 68.98±15.09 g and 79±17 cm^3, respectively.

All the measured and calculated properties were listed in Table 1.

In order to determine effective parameters on physical properties model, two-tailed correlations between bio-physical properties of the tomatoes were obtained using Pearson method (Table 2).

Table 1 Phisical properties of tomato fruits (V. Canyon, Early Ch)

Parameter	Average	Standard deviation	Coefficient of variation (%)
Fresh weight	68.98	15.09	21.87
Dry weight	9.15	2.16	23.59
Moisture	86.36	3.18	3.68
Volume	78.56	17.43	22.19
Density	0.88	0.04	4.96
Major diameter (mm)	47.55	3.76	7.91
Minor diameter (mm)	47.04	3.63	7.72
Length	52.33	4.35	8.32
Arithmetic mean diameter (mm)	48.97	3.79	7.73
Geometric mean diameter (mm)	48.91	3.78	7.72
Diameter of equivalent volume Sphere (mm)	52.83	4.20	7.94
Sphericity (dimensionless)	0.94	0.03	2.81
Poisson's Ratio	0.45	0.01	2.85
Modulus of elasticity	0.05	0.01	14.90
Rupture force (N)	57.85	9.14	15.80
Extension at rupture (mm)	10.52	1.44	13.70
Energy for rupture (N mm)	271.70	83.31	30.66

Table 2 Correlations among the physical properties

		FW	DW	M	V	ρ	D1	D2	L	AMD	GMD	DEVS	S	P	ME	RF	RE
DW	r	0.360															
	S	0.342															
M	r	0.621	–0.491														
	S	0.074	0.179														
V	r	0.973**	0.445	0.506													
	S	0.000	0.230	0.165													
ρ	r	0.143	–0.361	0.515	–0.091												
	S	0.714	0.339	0.156	0.816												
D1	r	0.952**	0.342	0.594	0.957**	0.013											
	S	0.000	0.368	0.092	0.000	0.974											
D2	r	0.956**	0.342	0.602	0.958**	0.025	0.996**										
	S	0.000	0.368	0.087	0.000	0.950	0.000										
L	r	0.956**	0.457	0.502	0.930**	0.132	0.864**	0.856**									
	S	0.000	0.217	0.169	0.000	0.734	0.003	0.003									
AMD	r	0.988**	0.398	0.582	0.980**	0.063	0.981**	0.978**	0.944**								
	S	0.000	0.289	0.100	0.000	0.872	0.000	0.000	0.000								
GMD	r	0.987**	0.392	0.586	0.980**	0.062	0.983**	0.981**	0.940**	1.000**							
	S	0.000	0.296	0.097	0.000	0.874	0.000	0.000	0.000	0.000							
DEVS	r	0.976**	0.481	0.495	0.994**	–0.049	0.961**	0.962**	0.943**	0.988**	0.987**						
	S	0.000	0.190	0.175	0.000	0.901	0.000	0.000	0.000	0.000	0.000						
S	r	–0.132	–0.258	0.094	–0.074	–0.232	0.122	0.140	–0.391	–0.065	–0.053	–0.094					
	S	0.734	0.503	0.810	0.851	0.548	0.754	0.720	0.298	0.869	0.892	0.809					
P	r	0.621	–.491	1.000**	0.506	0.515	0.594	0.602	0.502	0.582	0.586	0.495	0.094				
	S	0.074	0.179	0.000	0.165	0.156	0.092	0.087	0.169	0.100	0.097	0.175	0.810				
ME	r	–0.318	0.604	–0.830**	–0.226	–0.407	–0.264	–0.256	–0.318	–0.291	–0.292	–0.230	0.169	–0.830**			
	S	0.404	0.085	0.006	0.559	0.278	0.492	0.506	0.404	0.447	0.445	0.552	0.663	0.006			
RF	r	0.697*	0.749*	0.025	0.709*	–0.029	0.702*	0.716*	0.639	0.707*	0.706*	0.725*	0.055	0.025	0.406		
	S	0.037	0.020	0.949	0.032	0.941	0.035	0.030	0.064	0.033	0.033	0.027	0.888	0.949	0.278		
RE	r	0.607	–0.100	0.706*	0.471	0.600	0.457	0.471	0.629	0.543	0.541	0.501	–0.391	0.706*	–0.661	0.225	
	S	0.083	0.799	0.033	0.201	0.088	0.216	0.201	0.069	0.131	0.133	0.170	0.298	0.033	0.053	0.561	
E	r	0.589	0.137	0.457	0.481	0.468	0.376	0.393	0.658	0.503	0.497	0.501	–0.583	0.457	–0.400	0.362	0.916**
	S	0.095	0.724	0.216	0.190	0.203	0.319	0.295	0.054	0.168	0.174	0.169	0.100	0.216	0.286	0.338	0.001

Note: **. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Where: r is Pearson correlation; S is significance (2-tailed); FW is fresh weight; DW is dry weight; M is moisture; V is volume; ρ is density; D1 is major diameter; D2 is minor diameter; L is length; AMD is arithmetic mean diameter; GMD is geometric mean diameter; DEVS is diameter of equivalent volume sphere; S is sphericity; P is Poisson's ratio; ME is modulus of elasticity; RF is rupture; RE is rupture extension; and E is rupture energy.

As shown in Table 1, the correlation between major and minor diameters were very significant at the 0.01 level. The correlation between geometric diameter and fresh weight was very significant at the 0.01 level. Modulus of elasticity had a significant correlation with inverse of both fruit moisture and Poisson's ratio at the 0.01 level. Rupture force was significantly correlated with fresh weight, volume, dry weight, major diameter, minor diameter, arithmetic mean diameter, geometric mean diameter, and diameter of equivalent volume sphere at the 0.05 level.

Regression relations found in this study were shown in Figure 1. Regression equations between modulus of elasticity and inverse of both fruit moisture and Poisson's ratio were exponential ($ME=\alpha x^{\beta}$ with the coefficient of determination (R^2) of 0.70. The regression relations for physical properties had good coefficient of determination. Major diameter and minor diameter regression equations were linear with R^2=0.9921.

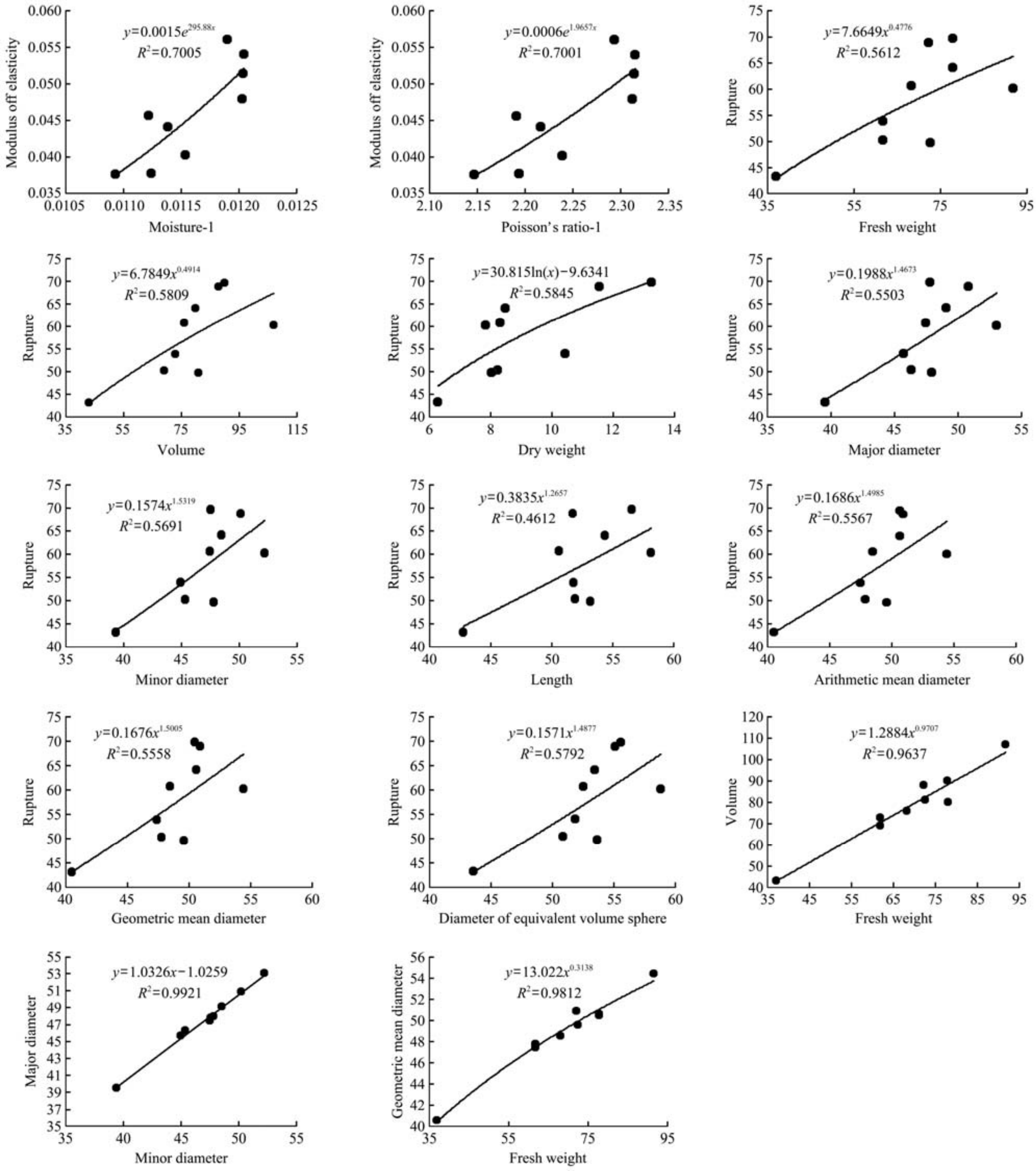

Figure 1 Regression equations among the correlated properties for tomato fruit

4 Discussion

The studied tomato fruits were within the thresholds (size (mean diameter): 45.75±5.38 mm and weight: 71.76±18.88 g) required for processing by the industry (Arazuri et al., 2007).

Among the properties given in Table 1, sphericity (2.81%) and density (4.96%) had the least amount of variability. The highest variability was shown in the value of rupture energy (30.66%). The reason may be the variability in the size of the fruits.

Physical properties of different tomato cultivars are not essentially the same. In a study on physical properties of other tomato variety (Momotaro), fresh weight was 157.78 g, major diameter was 70.97 mm, minor diameter was 70.10 mm, modulus of elasticity was 0.003780, and rupture force was 3.45 N (Sirisomboon et al., 2012); while in another study these parameters were different in varieties Fenguan906 and Jinguan28 (Li et al., 2011).

As seen in Table 1 and Figure 1, fresh weight of tomato fruits can be a good criterion to estimate their shape characteristics. So, volume, V (cm^3), of the tomatoes can be estimated based on the fruit's fresh weight (Equation (8)).

Estimation of density, ρ (g cm^{-3}), (Equation (9)) can be achieved by estimating fruit volume based on just one parameter (fresh weight). The regression equation for geometric mean diameter against fresh weight, W_f (g), with R^2=0.9812, and the relationship between geometric mean diameter and sphericity (D_V (mm) in Equation (5)) resulted in a new equation for estimation of sphericity based on tomato fresh weight (Equation (10)).

$$V=1.2884\times W_f^{0.9707} \tag{8}$$

$$\rho=0.7762\times W_f^{0.0239} \tag{9}$$

$$D_V=1.3501\times W_f^{0.3236} \tag{10}$$

Because of similarity of D_1 and D_2 and difference with L, this tomato fruits (v. Early Ch) can be described as ovate shape. While, major diameter, D_1 (mm), can be written as a function of minor diameter, D_2 (mm), as follows (Equation (11)).

$$D_1=1.0326\times D_2-1.0259 \tag{11}$$

Therefore, Equations (2), (3), and (5) can be written based on the results of this study as bellow.

$$D_a=0.6775D_2+\frac{L}{3} \tag{12}$$

$$D_g=\sqrt[3]{(1.0326\times D_2-1.0259)\times D_2\times L} \tag{13}$$

where, D_a is arithmetic mean diameter (mm); L is length (mm); D_g is geometric mean diameter (mm), and D_2 is minor diameter (mm).

Based on the significant correlations between rupture force and fruit fresh weight, volume, dry weight, major diameter, minor diameter, arithmetic mean diameter, geometric mean diameter, and diameter of equivalent volume sphere (Table 1), it was expected to find the existing equations. Nine regression equations were also developed (Figure 1), however, the resulting R^2 values were not very high. Therefore, it was presumed that rupture force can be a function of the following 9 parameters (Equation (16)).

$$F_R=f(W_f\cdot V\cdot W_d\cdot D_1\cdot D_2\cdot L\cdot D_a\cdot D_g\cdot D_v) \tag{16}$$

As shown in the Figure 1, F_R is proportional with $W_f^{0.4776}$, $V^{0.4914}$, $\ln(W_d)$, $D_1^{1.4673}$, $D_2^{1.5319}$, $L^{1.2657}$, $D_a^{1.4985}$, $D_g^{1.5005}$, and $D_v^{1.4877}$. Therefore, Equation (16) can be written as a function of mentioned parameters with different coefficients (Equation (17)).

$$F_R=\alpha_1W_f^{0.4776}+\alpha_2V^{0.4914}+\alpha_3\ln(W_d)+\alpha_4D_1^{1.4673}+\alpha_5D_2^{1.5319}+\alpha_6L^{1.2657}+\alpha_7D_a^{1.4985}+\alpha_8D_g^{1.5005}+\alpha_9D_v^{1.4877} \tag{17}$$

Equation (17) can be considered for all the measured F_R, so the matrix of F_R values was equal to internal matrix multiplication of coefficients (α values) on parameters (p values) (Equation (18)).

$$\begin{bmatrix}\alpha_{11} & \cdots & \alpha_{19}\\ \vdots & \ddots & \vdots\\ \alpha_{n1} & \cdots & \alpha_{n9}\end{bmatrix}\cdot\begin{bmatrix}p_1\\ \vdots\\ p_9\end{bmatrix}=\begin{bmatrix}F_{R1}\\ \vdots\\ F_{R9}\end{bmatrix} \tag{18}$$

Based on the data of study, and solving Equation (18), coefficients of the Equation (17) were listed in Table 3.

Table 3 Amounts of coefficients in the Equation (17)

Coefficient	Amount	Coefficient	Amount	Coefficient	Amount
α_1	283.7684	α_4	18.4863	α_7	143.7857
α_2	−753.259	α_5	−0.7469	α_8	−166.378
α_3	−93.9351	α_6	1.6512	α_9	19.7479

Finally, the suggested equation for estimating tomato rupture force was as below (Equation (19)):

$$F_R=283.7684\times W_f^{0.4776}-753.2590\times V^{0.4914}-93.9351\times\ln(W_d)+18.4863\times D_1^{1.4673}-0.7469\times D_2^{1.5319}+1.6512\times L^{1.2657}+143.7857\times D_a^{1.4985}-166.3780\times D_g^{1.5005}+19.7479D_v^{1.4877} \tag{19}$$

5 Conclusion

Biophysical properties of tomatoes (v. Early Ch) and their mutual relationships were reported in this paper. These properties included geometric parameters (major diameter, minor diameter, length, and volume) as well as mass, dry matter, and rupture force. Poisson's ratio, modulus of elasticity, energy at rupture point, density, arithmetic mean diameter, geometric mean diameter, diameter of equivalent volume sphere, and sphericity were also determined using the appropriate formulae.

Two-tailed correlations among tomatoes physical properties were studied. Regression equations were developed by relating the properties that had significant correlations. Based on the regression equations, all the presumed equations (Equations (1) to (6)) were modelled by using of the study data and new equations were suggested (Equations (8) to (19)).

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