TEKA Kom. Mot. i Energ. Roln. – OL PAN, 2011, 11c, 151–161

A COMPARISON OF MECHANICAL PARAMETERS OF TOMATO'S SKIN OF GREENHOUSE AND SOIL-GROWN VARIETIES

Izabela Kuna-Broniowska[1] Bożena Gładyszewska[2], Anna Ciupak[2]

[1]Department of Applied Mathematics and Informatics,
University of Life Sciences in Lublin, Akademicka 13, 20-950 Lublin, Poland
e-mail: izabela.kuna@up.lublin.pl
[2]Departments of Physics, University of Life Sciences in Lublin,
Akademicka 13, 20-950 Lublin, Poland
e-mail: bozena.gladyszewska@up.lublin.pl

Summary. The paper presents the results of studies concerning the Young's modulus, critical stress, Poisson's ratio and thickness determined for the skin of greenhouse tomato cultivars (Admiro and Encore), and soil-grown varieties (Polset and Surya) comparison. Multivariate analysis of variance and one-dimensional tests [Hinkelmann 2008] were carried out. With the contrasts application the greenhouse varieties were compared with soil-grown ones. The comparison inside both: the greenhouse and soil-grown groups were also conducted. The homogeneity groups containing the average values of defined mechanical parameters of the tomato skin were determined.

Key words: skin, tomato fruit, Young's modulus, Poisson's ratio, multivariate analysis of variance, average homogeneity groups.

INTRODUCTION

The need to define the fundamental characteristics of biological material, including its mechanical properties is mainly related to the evaluation of the final product. It seems to be especially important in the case of horticultural production. The scale of the considered problem is huge, due to the fact that fruits as well as vegetables are prone to damage at every stage of production [Dobrzański and Rybczyński, 2008, Machado 1999, Sargent 1992, Peleg 1984, O'Brien 1963]. Emerging loads and breaking stresses are a natural consequence of the above situation. Mechanical damage leads to products commercial value reduction while the physiological changes (e.g. softening) during the fruit and vegetables ripening affects the susceptibility to damage, in addition. Therefore, the outer surface of fruits and vegetables (peel) functions mainly as a protective barrier for the internal soft tissues, determines the physiological states of the whole product, and takes part in biochemical processes [Bargel and Neinhuis 2005, Andrews et al. 2002].

The basic physical parameters characterizing the plant material in terms of mechanical properties are Young's modulus, critical stress and Poisson's ratio [Mohsenin 1970].

The aim of this study was to determine the values and statistical dependence between the strength parameters set by the uniaxial tensile tests application for the skin of greenhouse and soil-grown tomato varieties, stored at 13˚C.

MATERIALS AND METHODS

The research material was a peel of greenhouse tomato varieties Encore and Admiro as well as the soil-grown's Surya and Polset cultivars, both stored at 13ºC.

In each measurement series 30 repetitions were performed. Tomato fruits were selected randomly from among that, which skin was dyed in the orange and did not have any visible external damage. The specimens shape was established as rectangular strips, which were cut longitudinally in order to make the layer of pulp the thinnest possible. A profiled, single-blade knife with a limiter, ensuring repeatability of the specimens thickness was used for the skin biopsy.

The sample thickness was measured with the optical microscope application at 5 points in the central part of the strip on both sides with the accuracy of ± 0.05 mm after which the average value was calculated. The samples length and width were measured with the use of a caliper with the ± 0.1 mm accuracy. To eliminate the effect of sample drying, each test was performed immediately after specimen preparation.

In each single measurement the value of the force *F*, which followed the specimen rupture, was registered.

The method of random markers was applied to determine Young's modulus and Poisson's ratio of the tomato's fruit skin. Its main advantage is that the obtained results are independent of the effects observed along the specimen's edges, which are close to the clamping grips of the testing machine. Mentioned method relies on the analysis of the image and the distance between points on the surface of the sample subjected to uniaxial stretching tests. The random marking method allows measurements at well-defined location of the skin segment, which enables to eliminate the limitations occurring in typical strength tests such as cutting the samples with constant middle cross-section [Gładyszewska 2007].

The experiment was conducted on the measuring position assigned for the determination of mechanical properties of biological material [Gładyszewska 2006]. Prepared samples were placed in clamping grips of the tensile machine, after which powdered graphite markers were randomly sprayed on the sample surface. A CCD camera equipped with a microscope lens allowed the specimen observation at 240 x 320 pixel resolution under 5x magnification. The images from the camera as well as the value of the tensile force corresponding to each image were downloaded to the computer.

The critical surface tension σ_k of a stretched specimen was determined using Eq. (1), with the cross-section *S* knowledge:

$$\sigma_k = \frac{F}{S}, \tag{1}$$

where: *F* [N] is a force value corresponding to destruction of a sample, $S = a \cdot b$, *a* and *b* [mm] specimen's thickness and width respectively.

Knowledge of the relative elongation in the direction of the x-axis ε_x for different stress values σ_x made it possible to determine the Young's modulus *E* (2):

$$E = \frac{\sigma_x}{\varepsilon_x}, \tag{2}$$

while the Poisson's ratio v was computed based on dependence (3):

$$v = -\frac{\varepsilon_y}{\varepsilon_x}, \tag{3}$$

where: ε_x is a relative elongation in the direction of the applied tensile force (-), ε_y is a relative elongation in a perpendicular direction to the applied force (-).

STATISTICAL ANALYSIS

The statistical analysis was processed with the Statistica 6 application and included Young's modulus E, Poisson's ratio υ, the critical stress σ_k and the thickness of the tomato fruit's skin determination for both: greenhouse Admiro and Encore and ground Surya and Polset varieties, stored at 13 ° C.

The distribution of Poisson's coefficient v, which is the ratio of longitudinal strain and transverse strain, was difficult to determine. The ratio of two independent variables with normal standard distributions has a Cauchy distribution [Feller 1966]. This bell-shaped, symmetrical distribution has a higher peak in the center and "fatter" tails in comparison with normal distribution. However, if two normal distributed variables have a nonzero mean, a form of their ratio distribution is more complicated [Hinkley 1969]. Under certain assumptions, the data can be transformed to produce a new variable with distribution close to normal distribution [Geary 1930]. Since the Cauchy distribution is similar to normal distribution, it can be assumed, that the distribution of Poisson's ratio will also be close to normal distribution. For this reason, the statistical tests were performed to examine the consistency between Poisson's ratio distribution and normal distribution. Normal distribution parameters μ and σ were determined based on a sample, and for this reason the Shapiro-Wilk test was used [Shapiro and Wilk 1965]. The type of deviation of Poisson's ratio distribution from normality was analyzed based on probability plots [Thode 2002].

The results of the Shapiro-Wilk test, performed at the significance level of 0.01, indicate that there are no grounds for rejecting the assumed normality of Poisson's coefficient v distribution.

Young's modulus is a function of four variables: the force F, strain ε_x, sample thickness a and width b. Determination of the Young's modulus density function requires knowledge of other variables distributions and does not necessarily lead to a normal distribution, which is demanded for most statistical tests. The hypothesis, based on Shapiro-Wilk test, assuming that the Young's modulus distribution is the normal distribution, was not rejected, therefore the assumption of Young's modulus normality is recognized as a fulfilled (Kuna-Broniowska et al. 2011).

Tomato fruits were stored for at least 14 days, however, due to the incompatibility of the period of measurement for the individual varieties only four common terms of measurement could be distinguished. The experiment was conducted in two-way cross-classification system. The factors were experimental cultivars (Admiro, Encore, Polset and Surya) and the length of storage period (harvesting day, 4th day, 11th day and 14th day of storage).

Following linear model was adopted:

$$y_{ijk} = \mu + \alpha_j + \beta_k + \alpha\beta_{jk} + e_{ijk} \quad ,$$

where:
y_{ijk} – value of selected determinant of tomato fruit peel,
α_j – effect of j-th variety, $j = 1,2,3,4$,
β_k – effect of k-th storage time length, $k = 1,2,3,4$,

$\alpha\beta_{jk}$ – interaction effect of varieties and shelf-life.

Three types of hypotheses concerning the parameters of the experimental model were tested:

1. Hypothesis assuming no significant diversity of the varieties due to the mechanical properties of processed tomato's fruit skins.
2. Hypothesis about no significant diversity of the storage periods due to the mechanical properties of processed tomato's fruit peels.
3. Hypothesis assuming no significant diversity of tested varieties storage periods due to the mechanical properties of processed tomato's fruit skins.

Table 1 presents the results of Wilks' multivariate tests of significance on which (at the level of significance $\alpha = 0.01$) significant variation of mechanical properties of tomato fruit peel because of the variety and storage time was found. It was also stated that the investigated tomato varieties diversify during storage time, taking into account mechanical properties of their peel (the importance of interaction). Additionally, changes in the mechanical properties values extend to them differently during storage. Thus, determining the degree of ripeness of tomato fruits on the basis of changes in Young's modulus or Poisson's ratio values, which are basic determinants defining the material properties, should be carried out separately for each variety. The result of multivariate testing indicates that a comparison of average strength properties is essential (Tab. 1). In order to determine which characteristics diversify significantly due to experimental factors one-dimensional tests were carried out. Table 2 shows the results of tests for the four studied tomato fruit peel parameters.

The null hypothesis for the Young's modulus, Poisson's ratio and skin thickness were rejected at the significance level of $\alpha = 0.01$, based on unidimensional testing. It indicates the presence of significant diversity for each of three skin parameters due to the variety and storage time (Tab. 2). Critical stress values were significantly different between varieties, but did not diverse significantly during studied storage periods (Table 2). For Young's modulus, Poisson's ratio, skin thickness and the critical stress a significant interaction between the variety of tomatoes and their storage time was observed, which is synonymous with the need to analyze temporal changes in values of mechanical parameters separately for each variety.

Table 1. Wilks' multivariate tests of significance for the four varieties of tomatoes stored at 13°C

Effect	Test	Value	F	Effect	Error	p
Absolute term	Wilks	0.007	16212	3	343	0.000
Variety	Wilks	0.258	69	9	835	0.000
Storage time	Wilks	0.554	25	9	835	0.000
Interaction Variety x Time	Wilks	0.790	3	27	1002	0.000

Table 2. Unidimensional tests for Poisson's ratio *v*, the skin thickness, the critical stress σ_k and Young's modulus *E*

Diversity sources	Degrees of freedom	**SS**	**MS**	**F**	**p**
Poisson's ratio *v*					
Absolute term	1	96.802	96.802	15702.712	0.000
Variety	3	3.121	1.040	168.760	0.000
Time	3	0.079	0.026	4.293	0.000
Variety x Time	9	0.171	0.019	3.086	0.000
Error	345	2.127	0.006		
Generally	360	5.49734			
Skin thickness					
Absolute term	1	200.564	200.564	10619.693	0.000
Variety	3	2.066	0.689	36.460	0.000
Time	3	2.117	0.706	37.358	0.000
Variety x Time	9	0.773	0.086	4.546	0.000
Error	345	6.516	0.019		
Generally	360	11.4318			
Critical stress σ_k					
Absolute term	1	45.180	45.180	1997.310	0.000
Variety	3	2.565	0.855	37.792	0.000
Time	3	0.166	0.055	2.442	**0.064**
Variety x Time	9	0.549	0.061	2.699	0.005
Error	345	7.804	0.023		
Generally	360	11.0494			
Young's modulus *E*					
Absolute term	1	5769.497	5769.497	6688.028	0.000
Variety	3	507.704	169.235	196.178	0.000
Time	3	10.598	3.533	4.095	0.007
Variety x Time	9	34.556	3.840	4.451	0.000
Error	326	281.227	0.863		
Generally	341	824.135			

SS – sum of squares, MS- average square, Test F- Snedecor test, p – empirical probability (a posteriori)

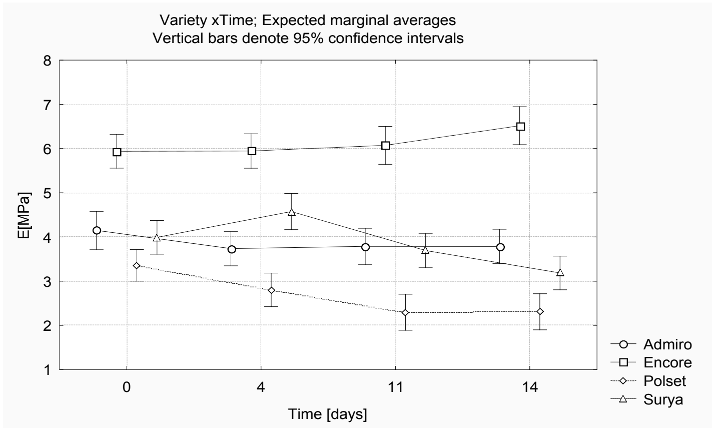

Fig. 1. The average values of Young's modulus in the selected four days of measurement

From the four tested tomato fruits cultivars, stored at 13 °C, the skin of Polset soil-grown cultivar was characterized by the lowest value of Young's modulus, while the highest one in the case of greenhouse Encore variety was received. Additionally, the value of the longitudinal modulus of elasticity for this variety increased with the growth of the storage time, while in the case of other varieties this value decreased in varying degrees (Fig. 1).

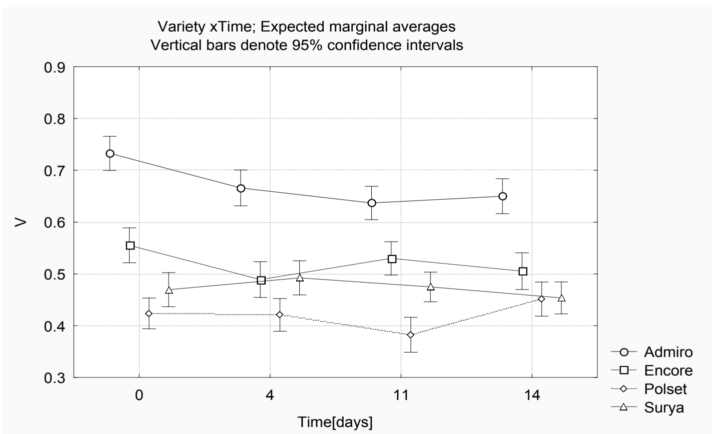

Fig. 2. Mean values of Poisson's ratio in the selected four days of measurement

The skin of greenhouse Admiro variety was characterized by the greatest value of Poisson's ratio *v*, while similar values of this parameter were observed in the case of the other 3 cultivars (Fig. 2).

The null hypotheses rejection for the studied mechanical properties of tomato fruit peel, indicates the significance of averages comparison in one case, at least. A study object was to compare the different varieties of soil-grown and greenhouse tomatoes. What is more, greenhouse Encore variety was compared with three others cultivars in the respect of Young's modulus E values while the Admiro variety with three other varieties on account of the Poisson's ratio v value. Four types of comparisons were defined by the following contrasts in order to carry out mentioned task:

1. Differences among both: the values of Poisson's ratio v ($\mu_{VE} - \mu_{VA}$) and Young's modulus E ($\mu_{EE} - \mu_{EA}$) for Admiro and Encore greenhouse tomato's fruit peel.
2. Differences among both: the values of Poisson's ratio v ($\mu_{ES} - \mu_{EP}$), and Young's modulus E ($\mu_{VS} - \mu_{VP}$) for soil-grown Polset and Surya tomato's fruit peel.
3. Differences between the values of Young's modulus E in the case of the Encore tomato variety with three other cultivars together: $3\mu_{EE} - (\mu_{EA} + \mu_{EP} + \mu_{ES})$.
4. Differences between the values of Poisson's ratio v determined for tomato skin of Admiro variety with three other cultivars together: $3\mu_{VA} - (\mu_{VE} + \mu_{VP} + \mu_{VS})$.

Table 3. Confidence intervals for selected comparisons between the average values of Poisson's ratio v and Young's modulus E

Comparison	**Poisson's ratio *v***					
	Evaluation	SE	t	p	Confidence boundaries -95%	Confidence boundaries 95%
$\mu_{VE} - \mu_{VA}$	-0.606	0.048	-12.520	0.000	**-0.701**	**-0.511**
$\mu_{VS} - \mu_{VP}$	0.212	0.046	4.649	0.000	**0.122**	**0.302**
$3\mu_{VA} - (\mu_{VE} + \mu_{VP} + \mu_{VS})$	2.409	0.117	20.640	0.000	**2.179**	**2.639**
Young's modulus *E*						
$\mu_{EE} - \mu_{EA}$	8.951	0.584	15.340	0.000	**7.803**	**10.099**
$\mu_{ES} - \mu_{EP}$	4.677	0.559	8.365	0.000	**3.577**	**5.777**
$3\mu_{EE} - (\mu_{EA} + \mu_{EP} + \mu_{ES})$	31.737	1.424	22.287	0.000	**28.936**	**34.539**

All comparisons considering average Poisson's ratio v values as well as Young's modulus E averages proved to be significant (Tab. 3). The Encore variety turned out to be different from the other three cultivars in the respect of Young's modulus values.

Admiro variety showed to be significantly different from the other three cultivars in the respect of Poisson's ratio v.

Both the greenhouse and soil-grown tomato varieties differ significantly among themselves in terms of Poisson's ratio and Young's modulus values.

Table 4. Homogeneous averages groups of Poisson's ratio; HSD (unequal N); Homogeneous group, α = 0.05; Error: intergroup MS = 0.00616, df = 345 (degrees of freedom)

Cell number	Variety	Time	Poisson's ratio *v*	1	2	3	4	5	6	7
			Averages							
10	Polset	11	0.382	****						
11	Polset	4	0.421	****	****					
12	Polset	0	0.424	****	****					
9	Polset	14	0.451	****	****	****				
13	Surya	14	0.454	****	****	****				
16	Surya	0	0.470		****	****				
14	Surya	11	0.475		****	****	****			
7	Encore	4	0.489		****	****	****			
15	Surya	4	0.492		****	****	****			
5	Encore	14	0.505		****	****	****			
6	Encore	11	0.530			****	****			
8	Encore	0	0.555				****	****		
2	Admiro	11	0.637					****	****	
1	Admiro	14	0.650						****	****
3	Admiro	4	0.666						****	****
4	Admiro	0	0.733							****

Table 4 contains homogeneous average groups of Poisson's ratio *v* for four tested cultivars determined in four selected days of storage. Seven homogeneous groups were identified. Admiro Variety, characterized by the highest values of Poisson's ratio created two homogeneous groups while other groups were formed by the averages for two or three varieties. The largest group consists with averages for Encore, Polset and Surya varieties, where, in the majority, the Surya averages occur.

Table 5. Homogeneous averages groups of Young's modulus E; HSD (unequal N); Homogeneous groups, $\alpha = 0.05$; Error: intergroup MS = 0.00616, df = 345 (degrees of freedom)

Cell number	Variety	Time	*E* Averages	1	2	3	4	5
11	Polset	12	2.297	****				
12	Polset	15	2.309	****				
10	Polset	5	2.803	****	****			
16	Surya	15	3.186	****	****	****		
9	Polset	1	3.360		****	****		
15	Surya	12	3.694		****	****	****	
2	Admiro	5	3.738		****	****	****	
4	Admiro	15	3.786			****	****	
3	Admiro	12	3.789		****	****	****	
13	Surya	1	3.991			****	****	
1	Admiro	1	4.149			****	****	
14	Surya	5	4.575				****	
5	Encore	1	5.879					****
6	Encore	5	5.944					****
7	Encore	12	6.073					****
8	Encore	15	6.517					****

The Tukey test (HSD) application allowed to distinguish five homogeneous averages groups of Young's modulus *E* for the four tested cultivars in four selected days of storage (Table 5). Encore variety, characterized by the highest values of Young's modulus parameter, created one homogeneous averages group. Other groups were formed by the averages for two or three varieties. The largest group consists of averages for Admiro, Polset and Surya varieties where, in the majority, the Admiro averages occur.

CONCLUSIONS

1. Young modulus, Poisson's ratio, thickness and critical stress values determined for the skin of tested tomato cultivars differentiate significantly with the duration of storage time.
2. Designated strength parameters were significantly dependent on the tested variety.
3. Comparative analysis revealed much greater variation of Young's modulus and Poisson's ratio values for greenhouse tomato fruit than in the case of soil-grown cultivars.

REFERENCES

1. Andrews J., Adams S. R., Burton K. S., Evered C. E. 2002.: Subcellular localization of peroxidase in tomato fruit skin and the possible implications for the regulation of fruit growth. *Journal of Experimental Botany 53 (378)*, 2185-2191.
2. Bargel H., Neinhuis C. 2005.: Tomato (*Lycopersicon esculentum Mill.*) fruit growth and ripening as related to the biomechanical properties of fruit skin and isolated cuticle. *Journal of Experimental Botany 56 (413)*, 1049-1060.
3. Dobrzański jr. B., Rybczyński R. 2008.: Właściwości fizyczne i biochemiczne materiałów roślinnych. Problemy pomiaru mechanicznych właściwości owoców w aspekcie oceny ich jędrności. Lublin: Wyd. Nauk. FRNA, Komitet Agrofizyku PAN.
4. Feller W. 1966. An introduction to probability theory and its applications", 2, Wiley.
5. Geary R.C. 1930.: The Frequency Distribution of the Quotient of Two Normal Variates". Journal of the Royal Statistical Society 93 (3), 442–446.
6. Gładyszewska B., 2007.: Method for testing selected mechanical properties of thin-film biomaterials (in Polish). Rozprawy Naukowe (325). Wydawnictwo Akademii Rolniczej, Lublin, 1-87.
7. Gładyszewska B. 2006.: Testing machine for assessing the mechanical properties of biological materials. *Technical Science 9*, 21-31.
8. Hinkelmann K. and Kempthorne O. 2008.: Design and Analysis of Experiments. Wiley.
9. Hinkley D. V. 1969. On the ratio of two correlated normal random variables. Biometrika 56 (3), 635-639.
10. Kuna - Broniowska I., Gładyszewska B., Ciupak A. 2011.: Storage temperature influence on Young modulus of tomato skin. *Teka Komisji Motoryzacji i Energetyki Rolnictwa – OL PAN,* (w druku).
11. Machado R. M., Rodriguez del Rincon A., Portas C. A. 1999.: Mechanical harvest of processing tomatoes: influence on percentage of damaged fruit and importance of the relation green fruit/rotten fruits. *Acta Horticulturae 487*, 237-241.
12. Mohsenin N. N. 1970.: Application of engineering techniques to evaluation of texture of solid food materials. *Journal of Texture Studies 1,* 133-154.
13. O'Brien M., Claypool L. L., Leonard S. J., York G. K., MacGillivray J. H. 1963.: Causes of fruit bruising on transport trucks. *Hilgardia 35 (6)*, 113-124.
14. Peleg K. 1984.: A mathematical model produce damage mechanisms. *Transactions of the ASAE 27 (1)*, 287-293.
15. Sargent S. A., Brecht J. K., Zoellner J. 1992.: Sensitivity of tomatoes at mature-green and breaker ripeness stages to internal bruising. *Journal of the American Society for Horticultural Science 117 (1)*, 119-123.
16. Shapiro S. S., Wilk M. B. 1965.: An analysis of variance test for normality (complete samples). Biometrika 52 (3-4), 591–611.
17. Thode H. C. 2002.: Testing for normality. New York: Marcel Dekker.

PORÓWNANIE PARAMETRÓW WYTRZYMAŁOŚCIOWYCH SKÓRKI OWOCÓW POMIDORA SZKLARNIOWEGO I GRUNTOWEGO

Streszczenie. Praca zawiera wyniki badań dotyczących porównania wartości modułu Younga, naprężenia krytycznego, współczynnika Poissona i grubości skórki owoców pomidora szklarniowego odmian Admiro i Encore oraz gruntowego odmian Polset i Surya. W tym celu przeprowadzona została wielowymiarowa analiza wariancji oraz testy jednowymiarowe (Hinkelmann 2008). Za pomocą kontrastów porównano odmiany szklarniowe z odmianami gruntowymi, przeprowadzono również porównania wewnątrz odmian szklarniowych i gruntowych. Wyznaczono także grupy jednorodne średnich wartości badanych parametrów skórki owoców pomidora.

Słowa kluczowe: skórka, owoc pomidora, moduł Younga, współczynnik Poissona, wielowymiarowa analiza wariancji, grupy jednorodne średnich.