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STORAGE TEMPERATURE INFLUENCE ON YOUNG MODULUS OF TOMATO SKIN

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Summary. Statistical analysis has been used to interpret results of studying Young modulus, critical stress vs. thickness of tomato skin of Admiro and Encore variety. The model has been based on the method of response surface regression. The possibility of prediction of Young modulus for tomato fruit stored at the temperatures 13 ºC and 21 ºC basing on changes of skin thickness and critical stress has been considered using determinant coefficient R^2 that corresponds to fitting accuracy of the model.

Key words: Young modulus, response surface, tomato fruit peel, strength of the material

INTRODUCTION

Studying mechanical properties of vegetable materials is based on the relation between the applied force and the strain caused by this action. This also allows to determine some important mechanical parameters such as Young modulus, critical strain, critical stress and Poisson ratio (Sitkei 1986).

According to the work of Voisey (1971) when calculating Young modulus one needs to assume that stress is proportional to strain and that the process is reversible. In the case of viscoelastic vegetable materials the above-mentioned conditions are rarely fulfilled. The author stresses however, that Young modulus (as experimentally determined) can be used for quantitative characterization of many vegetable products, because this parameter is independent of geometrical dimension of a sample (Dobraszczyk 1999).

Most often Young modulus is determined for small strains - occurring in compression or tension tests - as a tangent of slope angle from the stress-strain dependence in its linear region (Burgert 2006). In this way many results have been obtained for tomatoes (Matas 2004, Gladyszewska 2009), orange (Singh 2006), seed coats (Gladyszewska 2006), onions (Hole 2000), apples (Dobrzański 2003, Alamar 2008, Gladyszewska 2010). Kabas et al. (2008a) (Mohsenin 1980) studied Young modulus of tomatoes variety cherry, using Boussinesq method.

By the use of the one-axis strain method also other tomato skins have been studied and strong dependence on tomato variety has been reported (Voisey 1965, Hankinson 1979; Thompson 2001; Andrews 2002; Matas 2004; Bargel 2004; Bargel 2005; Gładyszewska 2009; Ciupak 2010a, 2010b).

MATERIALS AND METHODS

Post-harvest tomatoes were stored in a controlled environment chamber at two temperatures: 13 ºC and 21 ºC. In order to determine Young modulus in our experiments we applied the random markers method (Gładyszewska 2007) that allows to obtain results independent on sample edge deformation effects.

Each measurement was performed in 30 replications. The strips excised lengthwise from the skin of tomato fruits were measured with calipers to determine the length, width and thickness of samples before analysis. The rectangular-shaped samples had the length of 30 mm ± 0.1 mm and the width of 10 mm ± 0.1 mm. The thickness of each sample was measured under an optical microscope at 5 points in the central part of the strip on both sides. The sample was placed on a slide in the slit of a measuring table for observing its longitudinal section under an ocular microscope. Thickness was expressed as the average of 10 individual measurements with the accuracy of ± 0.05 mm.

The ends of the samples prepared directly before measurement were placed in the clamping grips of the tensile testing machine (Gładyszewska 2007). The fixed clamping grip was connected to the Megaton Electronic (AG&Co) KT-1400 tensometer with a force measurement range of 0-100 N, and the moving grip was flexibly connected to a transmission device for stretching the specimen. Using a CCD equipped with a microscope lens, the specimen was observed at 240x320 pixel resolution under 5x magnification.

The images of the stretched sample with graphite markers randomly sprayed on the sample surface and the value of the tensile force corresponding to each image were downloaded to the computer. The signal from the tensometer was transmitted to the computer with the use of an analogue-to-digital converter. The random marking method has fewer limitations and produces fewer errors than other techniques for testing the mechanical properties of biological materials. 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.

Critical stress was calculated as:

$$\sigma = \frac{F}{S} \tag{1}$$

where F [N] is a force value corresponding to the destruction of a sample, $S = a \cdot b$, a and b are thickness and width of a sample, respectively.

Knowing the strain ε_x for different stress σ one can calculate Young modulus:

$$E = \frac{\sigma}{\varepsilon_x} \tag{2}$$

where: ε_x – strain in the direction of the applied force.

The results were processed statistically using the Statistica 6 application.

RESULTS

Young's modulus is defined as a ratio of critical stress σ and strain in the direction of the applied force ε_x. Critical stress σ is a function of force value corresponding to destruction of a sample F[N] and cross-sectional area S, where $S = a \cdot b$, a and b are thickness and width of a sample, respectively. Thus, Young's modulus is a function of four variables: the force F, strain ε_x, and the thickness a and width b of the sample according to formula:

$$E = \frac{F}{a \cdot b \cdot \varepsilon_x}.$$

Determination of density function of Young's modulus requires knowledge of the distributions of other variables and does not necessarily lead to normal distribution, which is required for most statistical tests. Accordingly, there is no need to specify the density function module E, but only enough to apply the test of normality for the distribution of Young's modulus to verify the assumptions related to the method of analysis of variance. Normal distribution parameters were estimated based on a sample and hence the use of Shapiro –Wilk's test (Shapiro 1965). Type of derogation from the normal distribution of Young's module distribution was assessed by normality plots (Thode 2002).

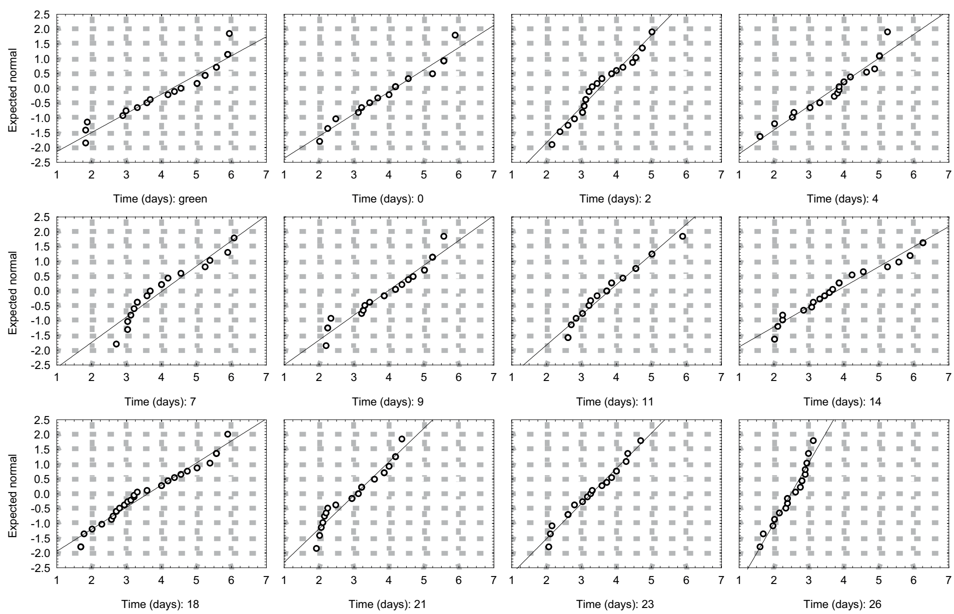


Fig. 1. Normal probability plots for Young modulus of the skin of greenhouse tomatoes cv. Admiro stored at 13°C.

Table. 1. Shapiro-Wilk test for Young's modulus

Test function	Period of storage (days)											
	green	0	2	4	7	9	11	14	18	21	23	26
Shapiro-Wilk	0.8998	0.9311	0.9488	0.9233	0.8948	0.9235	0.9429	0.9254	0.9483	0,9162	0.9581	0.9395
p- value	0.0346	0.2028	0.2557	0.0889	0.0556	0.1020	0.2715	0.0984	0.1522	0.0727	0.5350	0.2845

The results of Shapiro-Wilk test, performed at the significance level of 0.05, indicate that there are no grounds for rejecting the assumed normality of Young's modulus *E* distribution (all *p*-values are greater than 0.05) (Table 1).

Therefore, the assumption postulating a conformance between Young's modulus distribution and normal distribution seems to be fulfilled. The significance of variations in Young's modulus resulting from the studied tomato varieties, storage temperature and storage period can be examined by analysis of variance (Hinkelmann 2008). Due to space constraints, this paper presents the results of normality tests and normality plots solely for tomato fruit cv. Admiro stored at 13°C (Fig. 1).

Table 2. Univariate tests F for the Young's modulus of tomato fruit skin for two greenhouse tomato varieties

Sources of variation	SS	df	MS	F	p
Intercept	9094.21	1	9094.21	**10496.31**	0.00
Variety	155.37	1	155.37	**179.33**	0.00
Time of storage	166.99	5	33.40	**38.55**	0.00
Temperature	75.28	1	75.28	**86.88**	0.00
Variety*Time	29.99	5	6.00	**6.92**	0.00
Variety *Temperature	62.32	1	62.32	**71.92**	0.00
Temperature*Time	256.51	5	51.30	**59.21**	0.00
Variety * Temperature *Time	18.20	5	3.64	**4.20**	0.00
Error	389.89	450	0.87		

The results of the analysis of variance indicate significant differences in the mean Young modulus between varieties, temperature and storage time. Significant differences were also observed as regards interactions between the experimental factors (Table 2). Since the storage period of tomato fruits kept at various temperatures differed, further statistical analyses were carried out separately for each temperature regime. They investigated changes in Young modulus during storage and the option of modeling these changes based on stress and skin thickness values.

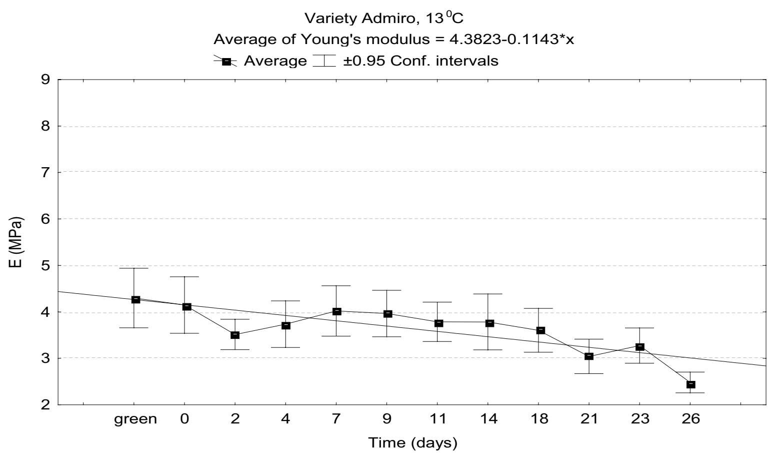
Table 3. Mean values of Young's modulus for tomato fruit skin cv. Encore and Admiro stored at 13 ºC and 21 ºC

Variety	Temperature	*E* Average	*E* Std. Error	*E* - 95.00%	*E* + 95.00%	N
Admiro	13 ºC	3.863	0.085	3.696	4.030	122
Admiro	21 ºC	3.791	0.086	3.621	3.960	117
Encore	13 ºC	5.743	0.086	5.574	5.912	119
Encore	21 ºC	4.213	0.087	4.042	4.384	116

The mean value of Young's modulus for tomato fruits cv. Admiro stored at the temperature of 13 ºC was 3.863 MPa, and it was a little higher in comparison with the fruit stored at 21 ºC. Tomato fruits cv. Encore were marked by higher differences in the mean values of Young's modulus which reached 5.743 MPa at 13°C and 4.213 MPa at 21°C (Table 3).

The changes in the value of Young's modulus of the skin of tomatoes cv. Admiro and Encore are shown in Fig. 2 and 3. In Admiro variety tomatoes stored at 13° C Young's modulus decreased from 4.15 MPa on harvesting day to 2.48 MPa after 26 days of storage (Fig. 2a), implying a 40% drop. As regards the fruits stored at 21°C, the values of Young's modulus decreased from 6.40 MPa on the harvesting day to 2.25 MPa after 12 days of storage (Fig. 3a).

The value of Young's modulus of the skin of tomato fruits cv. Encore stored at 13°C varied during the 28-day period of storage (Fig. 2b). In successive days of the study, the investigated parameter varied in the range of 3.73 MPa – 7.40 MPa. In the group of fruits stored at 21°C, the Young's modulus decreased from 5.79 MPa on the harvesting day to 2.98 MPa after 12 days of storage. (Fig. 3b).



a)

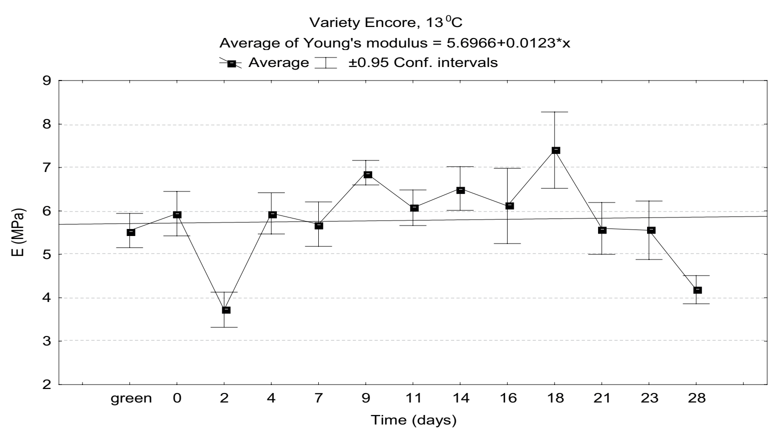


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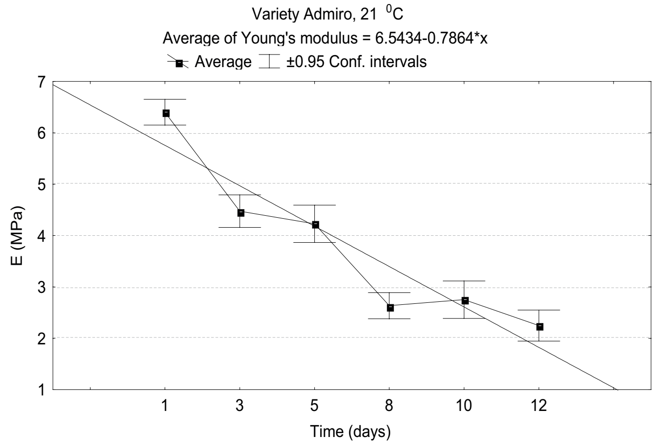
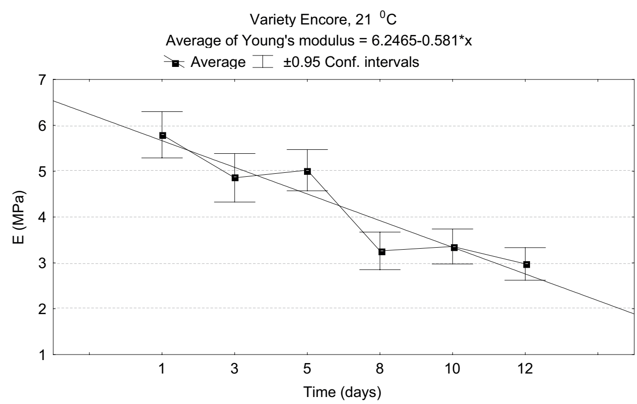
Fig. 2. Mean values of Young modulus of tomato fruit skin cv. Admiro (a) and Encore (b) stored at 13°C.



a)



b)

Fig. 3. Mean values of Young modulus of tomato fruit skin cv. Admiro (a) and Encore (b) stored at 21°C

Table 4. Results of univariate tests of significance for a model of Young's modulus of tomato fruit skin, cv. Admiro stored at 13°C

Effect	SS	df	MS	F	p
Intercept	018	1	0.18	0.18	0.67
Time	**40.19**	**11**	**3.65**	**3.57**	**0.00**
Thickness	0.04	1	0.04	0.04	0.84
Thickness ^{2}	0.08	1	0.08	0.07	0.78
Stress	**4.73**	**1**	**4.73**	**4.63**	**0.03**
Stress ^{2}	**6.94**	**1**	**6.94**	**6.79**	**0.01**
Thickness * Stress	0.14	1	0.14	0.13	0.71
Error	241.29	236	1.02		

A curvilinear dependence was observed between Young's modulus, storage time, critical stress and skin thickness. In the fitted model (all effects method), the linear components of time and the linear and quadratic component of stress were statistically efficient (Table 4).

Thickness of skin does not significantly influence the value of Young's modulus.

Table 5. SS test results for a complete model relative to SS for the residuals, cv. Admiro stored at 13°C

	Multiple R	Multiple R^2	Adjusted R^2	SS Model	df Model	MS Model	SS Resid.
E	0.52	0.27	0.22	88.90	16	5.56	241.30

Changes in Young's modulus *E* can be predicted in 22 % (adjusted R^2) based on storage time, changes in critical stress and skin thickness. The remaining 78% of changes of this magnitude are not determined by the examined characteristics. The produced model does not fit the experimental data (Table 5) well, and it cannot be used for predicting Young's modulus.

For variety Admiro stored at 21 °C the equation describing the dependence of Young's modulus on the storage time, stress and critical thickness of the skin is an equation of the quadratic order. In the fitted model (all effects method), the linear components of time and the linear and quadratic component of stress were statistically significant (Table 6). This is the same kind of relationship as the relationship that occurs in the model for the storage temperature equal to 13 ° C (Tab. 4).

Table 6. Results of univariate tests of significance for a model of Young's modulus of tomato fruit skin, cv. Admiro stored at 21 °C

Effect	SS	Degrees of freedom	MS	F	p
Intercept	0.21	1	0.21	0.58	0.45
Time	**66.92**	**5**	**13.38**	**37.68**	**0.00**
Thickness	0.67	1	0.67	1.88	0.17
Thickness ^{2}	0.44	1	0.44	1.23	0.27
Stress	**2.95**	**1**	**2.95**	**8.30**	**0.01**
Stress ^{2}	**1.85**	**1**	**1.85**	**5.21**	**0.02**
Thickness * Stress	1.32	1	1.32	3.73	0.06
Error	37.65	106	0.35		

Tabela 7. SS test results for a complete model relative to SS for the residuals, cv. Admiro stored at 21 °C

	Multiple R	Multiple R^2	Adjusted R^2	SS Model	df Model	MS Model	SS Resid.	df Resid.	MS Resid.	F	P
E	0.93	0.87	0.86	248.97	10	24.89	37.65	106	0.35	70.1	0.00

The model obtained during the study for the peel of tomato variety Admiro, which were stored at 21 ° C fits the experimental data very well (adjusted R^2).

Changes in Young's modulus reach about 86 % due to changes of the storage time, stress and critical thickness of the skin (Table 7). In this case, a better fitting of the model was obtained than for the same variety of fruit stored at 13 ° C (Table 5).

The results of significance tests for Poisson's ratio are presented in response surface charts. This study presents a single response surface chart which is the most consistent with the best fitted model (Fig. 4).

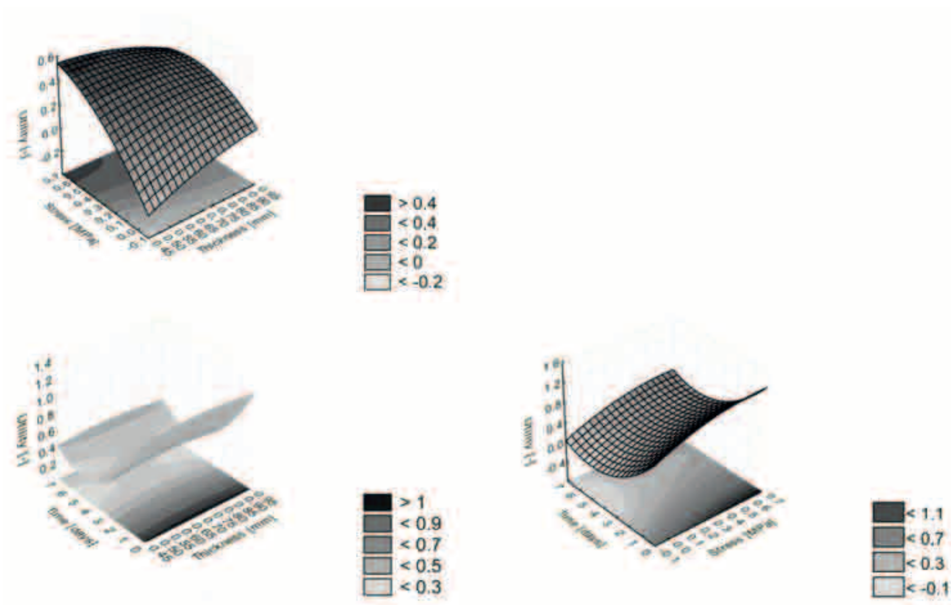


Fig. 4. Response surface - Contours for Young's modulus of tomato fruit skin, cv. Admiro stored at 21 °C

It can be assumed that the changes associated with the process of fruit ripening at room temperature, run more evenly than at 13 °C. In the summary of statistical analysis of the results obtained for the peel of tomato variety Admiro stored at two temperatures 13 °C and 21 °C it should be noted that there is need for further studies at different temperatures of storage, to determine the Young's modulus dependence on temperature conditions of storage. Changes in the value of determined parameters obtained for the skins of fruit stored at 13 °C generally proceeded without a clear trend of increase or decrease. It can not be stated unequivocally whether the reason for this is the temperature or other factors, not included in the study, which may affect the fruit firmness during storage in a climate chamber.

Table 8. Results of univariate tests of significance for a model of Young's modulus of tomato fruit skin, cv. Encore stored at 13 °C

Effect	SS	df	MS	F	p
Intercept	0.44	1	0.44	0.41	0.52
Time	**175.48**	**12**	**14.62**	**13.57**	**0.00**
Thickness	0.76	1	0.76	0.70	0.40
Thickness ^{2}	0.57	1	0.57	0.53	0.47
Stress	**7.58**	**1**	**7.58**	**7.03**	**0.01**
Stress ^{2}	**8.59**	**1**	**8.59**	**7.97**	**0.01**
Thickness * Stress	1.42	1	1.42	1.32	0.25
Error	240.34	223	1.08		

A curvilinear dependence was observed between Young's modulus, storage time, critical stress and skin thickness. This relationship can be described, due to the critical stress, as the polynomial of the quadratic order. In the fitted model, the linear components of time and the linear and quadratic component of stress were statistically efficient, thickness of skin did not significantly affect the value of elastic modulus (Tab. 8).

Table 9. SS test results for a complete model relative to SS for the residuals, cv. Encore stored at 13 °C

	Multiple R	Multiple R^2	Adjusted R^2	SS Model	df Model	MS Model	SS Resid.	df Resid.	MS Resid.	F	P
E	0.70	0.49	0.45	233.57	17	13.74	240.34	223	1.08	12.75	0.00

Changes in Young's modulus *E* can be predicted in 45 % (adjusted R^2) based on storage time, changes in critical stress and skin thickness. The remaining 55 % of changes of this magnitude are not determined by the examined characteristics (Tab. 9). The produced model does not fit the experimental data (Tab. 9) well, and it cannot be used for predicting Young's modulus for tomato fruit cv. Encore stored at 13 °C.

Table 10. Results of univariate tests of significance for model of Young's modulus of tomato fruit skin, cv. Encore stored at 21 °C

Effect	SS	Degrees of freedom	MS	F	p
Intercept	0.00	1	0.00	0.00	0.97
Time	**51.24**	**5**	**10.25**	**12.77**	**0.00**
Thickness	0.36	1	0.36	0.44	0.51
Thickness ^{2}	0.44	1	0.44	0.55	0.46
Stress	0.68	1	0.68	0.85	0.36
Stress ^{2}	0.05	1	0.05	0.06	0.8
Thickness * Stress	0.28	1	0.28	0.35	0.56
Error					

In the fitted model, only the component of time was statistically efficient, the other components did not have a statistically significant impact on the change of value of Young's modulus (Table 10).

Table 11. SS test results for a complete model relative to SS for the residuals, cv. Encore stored at 21 °C

	Multiple R	Multiple R^2	Adjusted R^2	SS Model	df Model	MS Model	SS Resid.	df Resid.	MS Resid.	F	P
E	0.79	0.63	0.60	144.30	10	14.43	84.28	105	0.80	17.98	0.00

The produced model for Young's modulus *E* of cv. Admiro stored at 21 °C fits the experimental data well. Changes in Young's modulus E can be predicted in 60% (adjusted R^2) based on storage time, changes in critical stress and skin thickness (Tab. 11). The fitting of this model is much better than of the model of the same variety, stored at 13 °C (Tab. 9)

Most likely, physiological and biochemical changes occurring during fruit ripening at the higher temperatures run more clearly than in the lower temperature.

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ANALIZA ZMIENNOŚCI MODUŁU YOUNGA SKÓRKI OWOCÓW POMIDORA W RÓŻNYCH TEMPERATURACH PRZECHOWYWANIA

Streszczenie. Praca zawiera analizę statystyczną w celu dopasowania modelu dla modułu Younga E na podstawie naprężenia krytycznego i grubości skórki owoców pomidora odmian Admiro i Encore. Dopasowanie modelu przeprowadzono metodą regresji powierzchni odpowiedzi. Możliwość prognozowania wartości E, owoców przechowywanych w temperaturze 13 ºC i 21ºC, na podstawie zmian grubości i naprężenia krytycznego ich skórki, określono na podstawie współczynnika determinacji R^2 wyrażającego stopień dopasowania modelu.

Słowa kluczowe: moduł Younga, powierzchnia odpowiedzi, skórka owocu pomidora, naprężenia materiału