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Effect of storage time and temperature on Poisson ratio of tomato fruit skin

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Abstract. The results of studies investigating the effects of storage time and temperature on variations in Poisson ratio of the skin of two greenhouse tomato varieties – Admiro and Encore were presented. In the initial period of the study, Poisson ratio of the skin of tomato fruit cv. Admiro, stored at 13°C, varied between 0.7 and 0.8. After the successive 10 days of the experiment, it decreased to approximately 0.6 and was stabilized until the end of study. By contrast, the skin of tomatoes cv. Encore was characterized by lower values and lower variability of Poisson ratio in the range of 0.4 to 0.5 during storage. The examinations involving tomato fruit cv. Admiro stored at 21°C were completed after 12 days due to fruit softening and progressive difficulty with preparing analytical specimens. The value of Poisson ratio for both varieties stored at room temperature fluctuated throughout the experiment to approximate 0.5.

Keywords: Poisson ratio, tomato fruit skin, response surface, strength of material

INTRODUCTION

A steady increase in fruit and vegetable crop areas enforces mechanical harvesting due to shortage of labour as well as short harvesting time. Mechanical harvesting methods exert load and breaking stress that cause damage to the harvested agricultural products. The physiological changes in maturing fruit and vegetables also contribute to the skin susceptibility to damage and pathogen infestation. The skin is the outermost layer in fruit that protects its soft tissue. The mechanical properties of the skin are an important consideration that affects the quality of the end product, product storage, processing and the design of machines and devices used in the production process (Gao and Pitt, 1991; Hertog *et al*., 2004).

The direct determination of Poisson ratio poses difficulties owing to the metamorphic structure of plant cells and their anisotropic and non-homogenous character. Poisson ratio can be determined by axially compressing or stretching samples or entire fruit specimens. The strain in the direction of the applied force and the strain in a perpendicular direction to the applied force are then measured (Moarcas and Irle, 1999; Wojciechowski, 2002).

For naturally occurring isotropic materials, the value of Poisson ratio is generally adopted in the range of 0-0.5 (Chung *et al*., 2004; Etnier, 2003) or $0.25 < v < 0.5$ with a theoretical boundary equal to -1. According to Steffe (1996), Poisson ratio for the majority of biological materials falls in the range of 0.2 to 0.5, while Tilleman *et al*. (2004) have suggested values in the range 0.25-0.85.

Liu *et al*. (2006) have observed that since Poisson ratio can be determined for delicate biological tissue, this parameter can play a key role in identifying the mechanical parameters of structural elements in plants. The main problem encountered in the identification of Poisson ratio for thin-layered plant materials, including fruit skin, is the determination of the sample longitudinal and transverse strain.

Kabas *et al.* (2008) determined Poisson ratio for cherry tomatoes by measuring the longitudinal and transverse strain of a compressed sample. The applied mathematical formula involved the determination of the fruit height and diameter before and after the experiment.

Homza *et al*. (2006) observed stretched corn root samples with the use of a digital camera. The method of random markers (Gładyszewska, 2006; 2007) was applied to determine Poisson ratio for the seed coat of beans (0.6-0.9) and faba beans (0.3-0.4) at different levels of natural hydration. Gładyszewska and Stropek (2010) measured the discussed parameter in the skin of apples cv. Topaz (0.4-0.7). The method of random markers was also used to determine Poisson ratio for tomato skin (0.40-0.73) (Gładyszewska and Ciupak, 2009). In fruit, the skin is an outermost layer that

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protects the flesh from external damage (De los Reyes, 2007; Telis, 2004). The determined strength parameters constitute a basis for assessing the fruit physiological condition.

The aim of this study was to analyze the impact of storage conditions of greenhouse tomato fruit on changes in Poisson ratio of tomato skins.

MATERIALS AND METHODS

Post-harvest tomatoes were stored in a controlled environment chamber at two temperatures: 13 and 21°C for 28 and 12 days, respectively. Tomato fruits have a longer storage life at lower temperatures, therefore, the period of storage at 13°C was 26 and 28 days and at 21°C – 12 days.

The test were performed in a laboratory for testing the mechanical properties of biological materials. The random marking method was applied to determine Poisson ratio of the skin (Gładyszewska, 2007). This method relies on the analysis of the image of randomly distributed markers on a sample surface and the changes of a distance between them when a sample is under uniaxial tensile stress. Poisson ratio is determined based on the sample strain, ε_x, in the direction of the applied force and the transverse direction, ε_y.

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 the samples before analysis. The rectangular-shaped samples had the length of 30 ± 0.1 mm and the width of 10 ± 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 samples prepared directly before measurement were placed in the clamping grips of tensile testing machine. 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 camera 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 edges which are close to the clamping grips of the testing machine.

The results were processed statistically using the Statistica 6 application.

The distribution of Poisson coefficient, which is the ratio of longitudinal strain and transverse strain, is 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 ratio will also be close to normal distribution. For this reason, the statistical tests were performed to examine the consistency between Poisson 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 ratio distribution from normality was analyzed basing on probability plots (Thode, 2002).

RESULTS AND DISCUSSION

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 coefficient v distribution (all p-values are greater than 0.01) (Table 1). Normal probability plots show a minor flattening of Poisson coefficient distribution curve in all studied periods and a slight right-sided asymmetry in the results obtained after 23 days of storage, but the noted deviations were not statistically significant (Fig. 1). 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, however the other considered cultivar also fulfills the normality condition at the significance level 0.05. Therefore, the assumption postulating a conformance between Poisson coefficient distribution and normal distribution seems to be fulfilled. The significance of variations in Poisson ratio resulting from the studied tomato varieties, storage temperature and storage period can be examined by analysis of variance (Hinkelmann and Kempthorne, 2008).

The values reported on successive days of the 14-day storage period were used to determine the effect of storage temperature and storage time on the mean values of Poisson ratio of the skin of two greenhouse tomato varieties. The results of an analysis of variance indicate significant differences in the mean Poisson ratio 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

Table 1. Shapiro-Wilk test for Poisson ratio

Test function	Period of storage (days)											
	green	0	2	4	7	9	11	14	18	21	23	26
Shapiro-Wilk	0.880	0.922	0.929	0.929	0.936	0.940	0.925	0.910	0.916	0.938	0.909	0.949
p-value	0.022	0.083	0.083	0.152	0.149	0.197	0.083	0.055	0.032	0.261	0.062	0.319

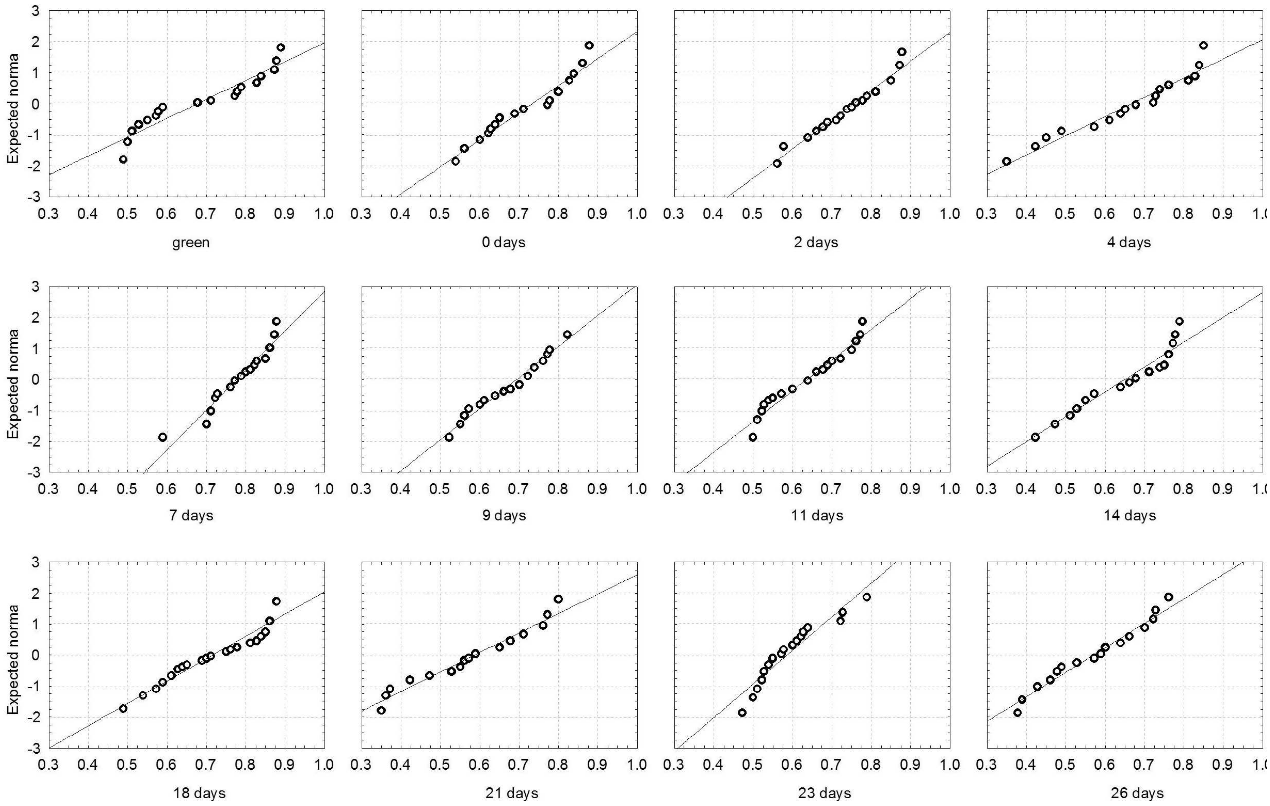

Fig. 1. Normal probability plots for Poisson ratio of the skin of greenhouse tomatoes cv. Admiro stored at 13°C.

analyses were carried out separately for each temperature regime. They investigated changes in Poisson ratio during storage and the option of modeling these changes based on stress and skin thickness values.

The mean value of Poisson ratio for tomato fruits var. Admiro stored at a temperature of 13 ºC was 0.71, and it was much higher in comparison with the fruit stored at 21ºC. Tomato fruits cv. Encore were marked by smaller variations in the mean values of Poisson ratio which reached 0.530 at 13°C and 0.477 at 21°C (Table 3). The changes in the value of Poisson ratio of the skin of tomatoes cv. Admiro and Encore are shown in Figs 2 and 3. In Admiro variety tomatoes stored at 13°C decreased from 0.73 on harvesting day to 0.57 after 26 days of storage (Fig.2a), implying a 22% drop. As regards the fruits stored at 21°C, the values of Poisson ratio remained stable in the range of 0.46-0.47 throughout the storage period (Fig. 3a).

The value of Poisson ratio of the skin of tomato fruits cv. Encore stored at 13°C varied during the 28-day period of storage (Fig. 2b). A decrease from 0.56 on harvesting day to 0.43 on the last day of storage was observed. In the group of fruits stored at 21°C, the Poisson ratio reached 0.53 after 24 h of storage. In successive days of the study, the investigated parameter varied in the range of 0.45-0.47 (Fig. 3b).

It is necessary to mention at this point that values of Poisson ratio higher than 0.5 should not be considered as being beyond mechanical limits. When isotropic 3D materials are considered, the limit $-1 \le \nu \le 0.5$ is valid. However, when a 2D medium is considered, the limit becomes $-1 \le \nu \le 1$. Moreover, when anisotropic media are considered there is in fact no limits for Poisson ratio (Wojciechowski, 2002). Thin fruit skin samples discussed in this work should be considered as close to 2D objects and surely are anisotropic

Table 2. Univariate tests F for the Poisson ratio of tomato fruit skin for two greenhouse tomato varieties

Sources of variation	SS	df	MS	F	p
Intercept	158.69	1	158.69	26 264.45	0.00
Variety	0.95	1	0.95	157.10	0.00
Temperature	2.92	1	2.92	482.68	0.00
Time of storage	0.18	5	0.04	5.89	0.00
Variety x Temperature	1.22	1	1.22	201.33	0.00
Variety x Time	0.13	5	0.03	4.41	0.00
Temperature x Time	0.14	5	0.03	4.60	0.00
Variety x Temperature x Time	0.09	5	0.02	3.05	0.01
Error	3.09	512	0.01		

Table 3. Mean values of Poisson ratio for tomato fruit skin cv. Encore and Admiro stored at 13 and 21°C

Variety	Temperature (°C)	*v*				N
		Average	SE	-95%	+95%	
Admiro	13	0.710	0.007	0.697	0.723	132
	21	0.466	0.007	0.453	0.480	127
Encore	13	0.530	0.007	0.516	0.543	142
	21	0.477	0.007	0.465	0.490	135

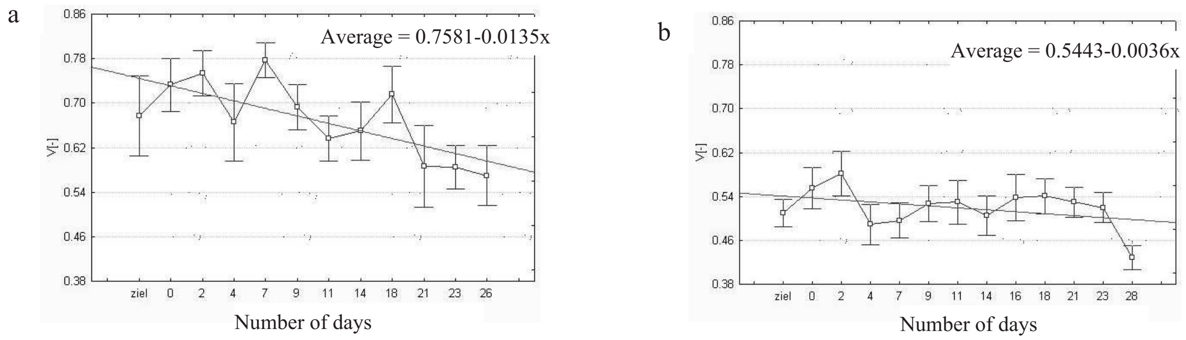

Fig. 2. Mean values of Poisson ratio of tomato fruit: a – skin cv. Admiro, b – Encore stored at 13°C; \ – average, ⇇ –± confidence intervals.

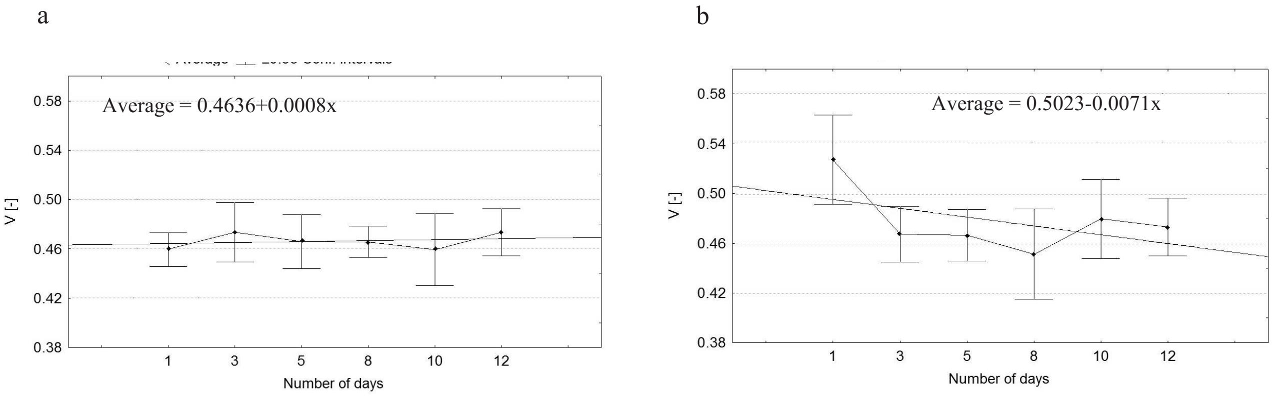

Fig. 3. Mean values of Poisson ratio of tomato fruit skin: a – cv. Admiro, b – Encore stored at 21°C. Explanations as in Fig. 2.

media. This cause that Poisson ratio for some samples is well higher than a standard mechanical limit for isotropic 3D media equal to 0.5.

A curvilinear dependence was observed between Poisson ratio, storage time, critical stress and skin thickness for tomato fruits cv. Admiro stored at 13°C. In the fitted model (all effects method), only the linear component of time was statistically efficient (Table 4). The results of fitting model for Poisson ratio are presented in response surface charts (Fig. 4). Changes in Poisson ratio can be predicted in 24% (adjusted R^2) based on storage time, changes in critical stress and skin thickness. The remaining 76% of changes of this magnitude are not determined by the examined characteristics. The produced model does not fit the experimental data well, and it cannot be used for predicting Poisson ratio. Also for tomato fruits cv. Encore stored at 13°C a curvilinear dependence was observed between Poisson ratio, storage time, critical stress and skin thickness. Similarly, in the fitted model (all effects method), only the linear component of time was statistically efficient. The results of significance tests for Poisson ratio are presented in response surface charts. In this study a single response surface chart which is most consistent with the best fit model is presented in Fig. 4. Changes in Poisson ratio can be predicted in 15% (adjusted R^2) based on storage time, changes in critical stress and skin thickness. The remaining 85% of changes of this magnitude are not determined by the examined characteristics. The produced model does not fit the experimental data well, and it cannot be used for predicting Poisson ratio for tomato fruit cv. Encore.

The following tables demonstrate the results of tests investigating the model and its goodness of fit with the data characterizing the tomato fruit stored at 21°C. In the fitted model of Poisson ratio of tomato fruit skin, cv. Admiro stored at 21°C, only the linear and quadratic components of thickness were statistically efficient. The model accounting for the impact of all predictors on Poisson ratio v does not fit the experimental data well. The values of Poisson ratio cannot be predicted on the basis of storage time, changes in critical stress and skin thickness. Only 7% of changes in Poisson ratio were determined by variations in the examined predictors. In the fitted model of Poisson ratio of tomato fruit skin, cv. Encore stored at 21°C, the linear component of time and the linear and quadratic components of thickness were statistically efficient.

The values of Poisson ratio for tomato fruit cv. Encore stored at 21°C cannot be predicted on the basis of storage time, changes in critical stress and skin thickness. Only 8% of the reported variability was attributable to changes in the value of the examined predictors.

Table 4. Results of univariate tests of significance for model of Poisson ratio of tomato fruit skin, cv. Admiro and Encore stored at 13 and 21°C

Effect	Admiro					Encore				
	SS	Degrees of freedom	MS	F	p	SS	Degrees of freedom	MS	F	p
					13°C					
Intercept	0.08	1	0.08	6.22	0.01	0.06	1	0.06	9.86	0.002
Time	0.85	11	0.08	6.08	0.00	0.33	12	0.03	4.92	0.00
Thickness	0.01	1	0.01	0.84	0.36	0.00	1	0.00	0.06	0.81
Thickness 2	0.03	1	0.03	2.37	0.12	0.00	1	0.00	0.19	0.66
Stress	0.00	1	0.00	0.08	0.77	0.00	1	0.00	0.00	0.98
Stress 2	0.00	1	0.00	0.03	0.87	0.00	1	0.00	0.01	0.92
Thickness x Stress	0.00	1	0.00	0.29	0.59	0.000	1	0.00	0.00	0.97
Error	3.10	244	0.01			1.44	255	0.01		
					21°C					
Intercept	0.04	1	0.04	17.44	0.00	0.00	1	0.00	0.26	0.61
Time	0.005	5	0.00	0.49	0.78	0.09	5	0.02	3.75	0.00
Thickness	0.01	1	0.01	6.22	0.01	0.02	1	0.02	4.05	0.05
Thickness 2	0.02	1	0.02	7.12	0.01	0.02	1	0.02	4.53	0.03
Stress	0.00	1	0.00	0.08	0.78	0.00	1	0.00	0.45	0.51
Stress 2	0.00	1	0.00	0.03	0.86	0.00	1	0.00	0.35	0.55
Thickness x Stress	0.00	1	0.00	0.20	0.66	0.01	1	0.01	1.68	0.20
Error	0.26	121	0.00			0.60	131	0.01		

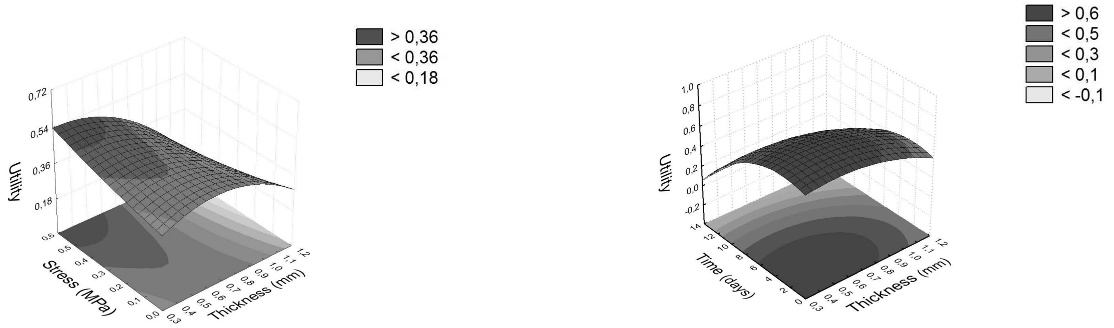

Fig. 4. Response surface – contours for Poisson ratio of tomato fruit skin, cv. Admiro stored at 13°C.

CONCLUSIONS

1. Changes of the considered parameters do not support the prediction of Poisson ratio. Tomato skin constitutes biological material whose structure changes in the course of biochemical processes during fruit ripening and storage.

2. A comprehensive model accounting for all parameters, including skin thickness, critical stress and storage temperature, did not produce a satisfactory goodness of fit. For the purpose of determining the ripeness of stored fruit based on changes in Poisson ratio over time, further research is required at different storage temperature regimes.

3. The results of this study suggest that the physiological changes and biochemical processes are more uniform in ripening fruit stored at a temperature of 21°C than those stored at 13°C.

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